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THE TRADE-OFF BETWEEN COLLECTOR AREA, STORAGE VOLUME, AND BUILDING CONSERVATION IN ANNUAL STORAGE SOLAR HEATING SYSTEMS

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PREFACE

This document is part of a coordinated effort at the Solar Energy Research Institute (SERI) to examine all aspects of energy storage technologies with applications in solar systems. A comprehensive study is presented of the performance of active solar space and water heating systems with intermediate and annual-cycle thermal energy storage. A unique feature of this report is the investigation of systems used to supply backup heat to passive solar and energy-conserving buildings, as well as to meet standard building loads.

The author extends his appreciation to Frank Baylin, who supervised the research leading to this report and provided valuable advice in its preparation, and to Michael Holtz, David Claridge, and Charles Wyman who critically reviewed this work.

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SUMMARY

OBJECTIVE

Develop a comprehensive understanding of the performance of active solar heating systems with intermediate and annual-cycle storage.

DISCUSSION

A daily-step computer simulation is used to determine the performance of solar heating systems as collector and storage size is varied. Simulations are performed for systems in four cities in the United States: Boston, Mass., Medford, Oreg., Bismarck, N. Dak., and Albuquerque, N. Mex. The study assumes various building load types and includes both flat-plate and evacuated-tube collectors at different tilt angles, and single-tank and two-tank systems. A unique feature of this study is the investigation of systems used to provide backup heat for passive solar and energy-conserving buildings and to meet standard building loads.

CONCLUSIONS AND RECOMMENDATIONS

System performance is found to increase linearly as storage size increases up to the point where the storage tank is large enough to store all surplus heat collected in summer. This point of unconstrained operation represents the optimum design for annual storage systems. Only a moderately-sized storage tank is needed for these systems if building loads have been reduced by conservation. In contrast to diurnal storage systems, annual storage systems show only slightly diminishing returns as overall system size is increased. Annual storage systems providing nearly 100% solar space heat may be economically preferable to the more common 50% solar heating systems with diurnal storage. Also, in contrast to diurnal systems, annual storage systems perform well in meeting the load of a passive solar or energy-efficient building. Economic analysis is based on the net energy added by the inclusion of annual storage in the solar heating system. This net added energy is found to be 130-210 MJ/m^3-yr, depending on location and load type. An assumed storage cost of \$30/m^3 is equivalent to a fuel price of 4¢-6¢/kWh. The entire system is found to be equivalent to a current fuel price of 4¢-9¢/kWh.

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SECTION 1.0

INTRODUCTION

1.1 OVERVIEW

Active solar energy is the major alternative heat source for building applications for which passive solar energy is unsuited or limited in its application. Active solar energy uses include hot water, space heat for residential, commercial and industrial buildings, backup heat for houses using passive solar heat in northern locations, and retrofit applications. The technical performance of active solar systems is limited by seasonal weather patterns. Because summer, the season of maximum sunlight, is also the time of minimum heat demand, active solar systems must either be undersized in meeting the load or sit idle during a large part of the year. In addition, backup energy is required during cloudy periods.

The use of annual storage both improves the technical efficiency of active solar systems by allowing collection of solar heat in summer and extends the capability of active solar systems to meet nearly 100% of the load. Annual storage systems rely on a large storage tank, usually with water as the storage medium. The storage tank is charged fully during summer, and the stored heat then is used to help meet the winter load. In addition, collection of solar heat continues during the winter, and the annual storage tank is used for day-to-day storage. The winter load, thus, is met partly by day-to-day collection of solar heat, as in a conventional active solar heating system, and partly by stored heat from the summer.

This work presents a comprehensive study of the design trade-offs in annual storage systems—particularly the trade-off between collector and storage size. A unique feature of this study is the investigation of systems with several types of building loads, including both space heat and hot water loads, and various conservation measures. Also included is a study of "hybrid" buildings that include both passive solar design and active solar heating with seasonal storage. Previous work in the field has been limited by the locations examined, collector type used, or extent of the design trade-offs considered (McGarity 1979; Baylin and Sillman 1980; Braun and Duffie 1979).

1.2 FUNCTIONING OF SEASONAL STORAGE SYSTEMS

The operation of seasonal storage systems can be understood by examining the annual building load and solar collection pattern (Fig. 1-1). Without seasonal storage, the system referred to would dump excess heat throughout the summer months and require backup heat to meet the difference between solar collection and building load in the winter months. Adding an annual storage tank would enable summer excess to be stored and used to provide winter backup. The necessary amount of annually stored heat is determined by the seasonal variation in load and solar heat supply.

While adding an annual storage tank to a system has the primary effect of matching the seasonal pattern of the heat supply with the load, it also has a secondary effect of reducing collector operating efficiency for large parts of the year. Figure 1-2 illustrates the difference in operating efficiency between an annual storage system and the equivalent active solar heating system with daily storage. Throughout the fall and winter, annual storage systems operate at higher temperatures and lower collector efficiency than

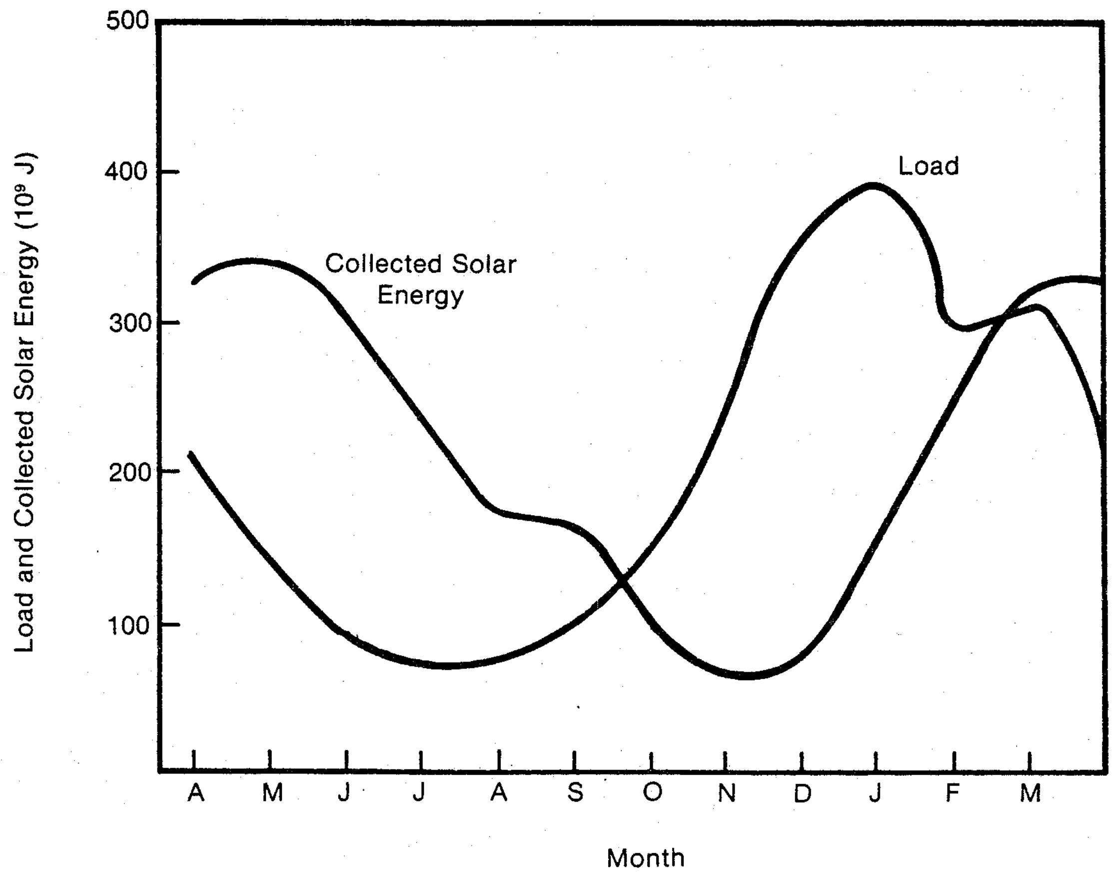
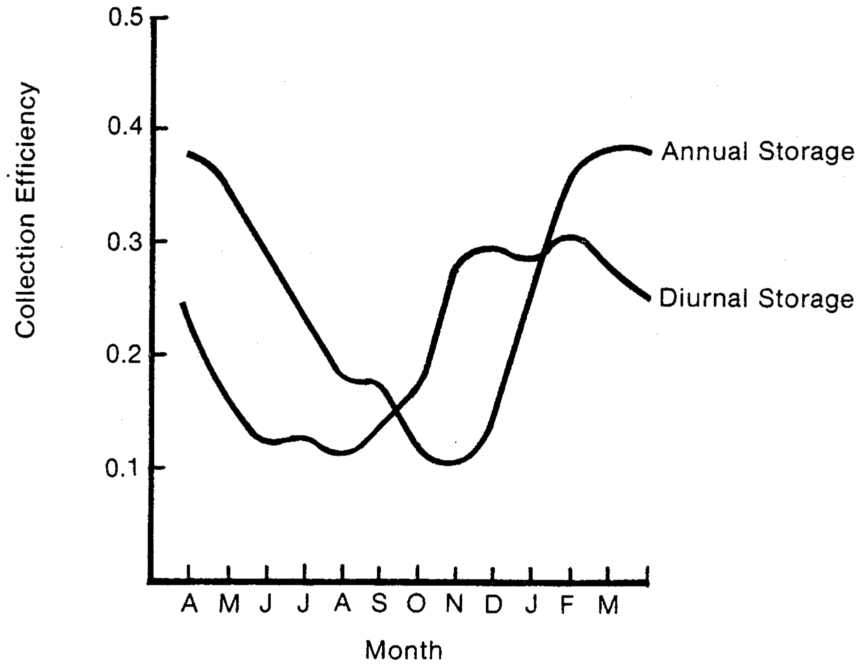
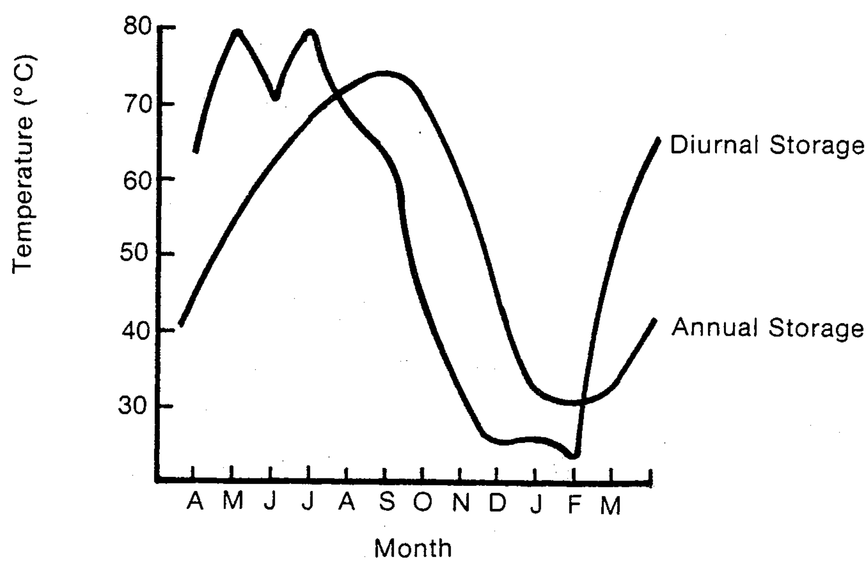


Figure 1-1. Profile of Monthly Load and Solar Collection for an Annual Storage System

System is designed to provide space and water heat for a 50-unit district of apartments in Boston, Mass. System uses flat-plate collectors. Data are all based on computer simulations.



(a) System Efficiency



(b) End-of-Month Storage Temperature

Figure 1-2. Monthly Collection Efficiency and End-of-Month Storage Temperature for Diurnal and Annual Storage Systems
Systems are designed for Boston, Mass., using flat-plate collectors.

systems with daily storage. Only in the spring and summer, when energy is not needed, does the collector efficiency of the annual system exceed that of the system with daily storage [see Fig. 1-2(b)]. Other effects of seasonal storage include greater storage losses and decreased day-to-day variation.

The reduction in efficiency with annual storage systems may be avoided by using a two-tank system, developed by Cha et al. (1979). This system operates with two storage tanks, one sized for daily storage and one sized for annual storage, enabling the system to store extra heat in the annual storage tank and simultaneously collect and use low-temperature heat during the fall and early winter. Figures 1-3 and 1-4 illustrate system operation and efficiency of the two-tank system, which combines advantages of both daily and annual storage systems.

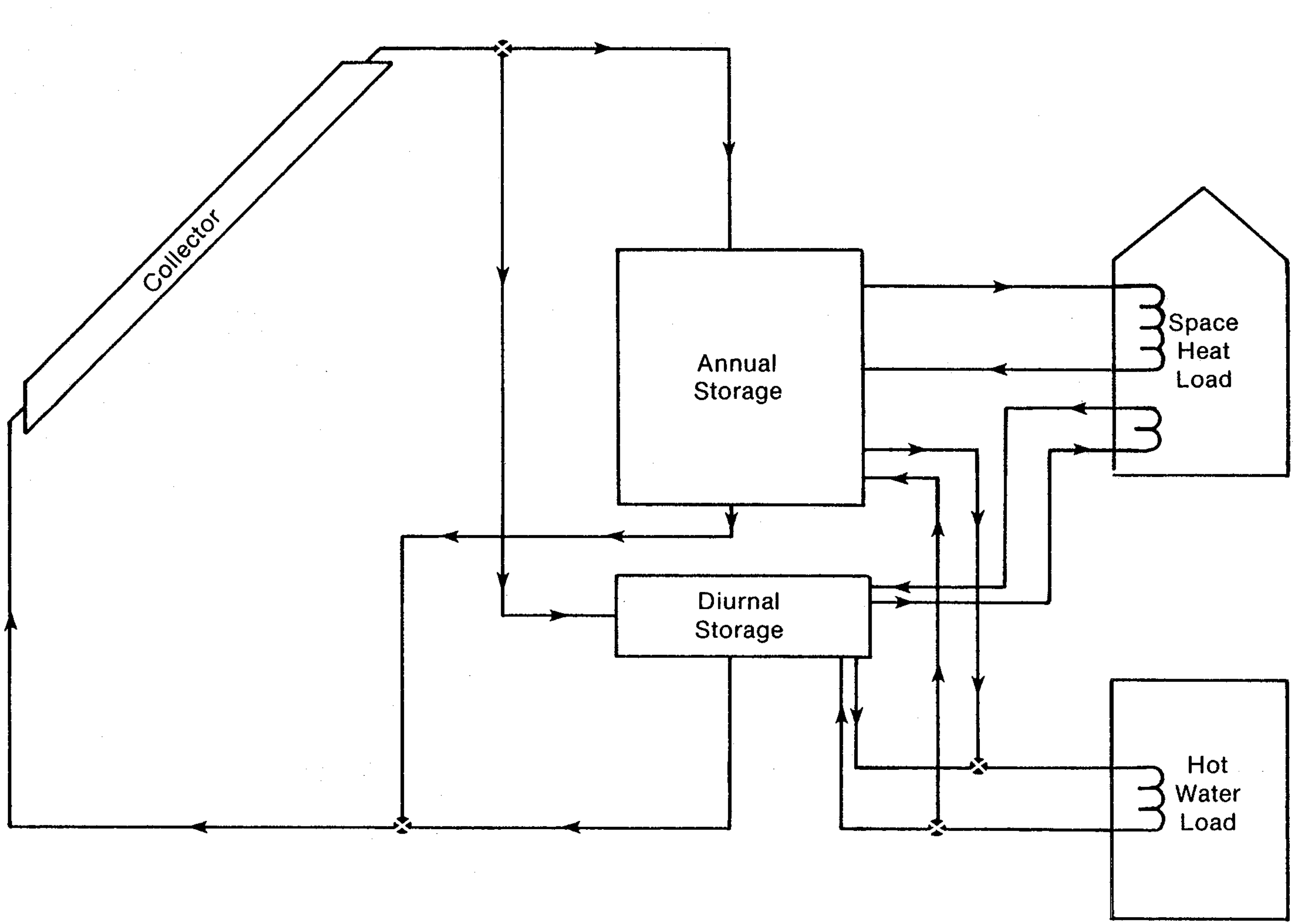


Figure 1-3. Schematic of Two-Tank Annual Storage System

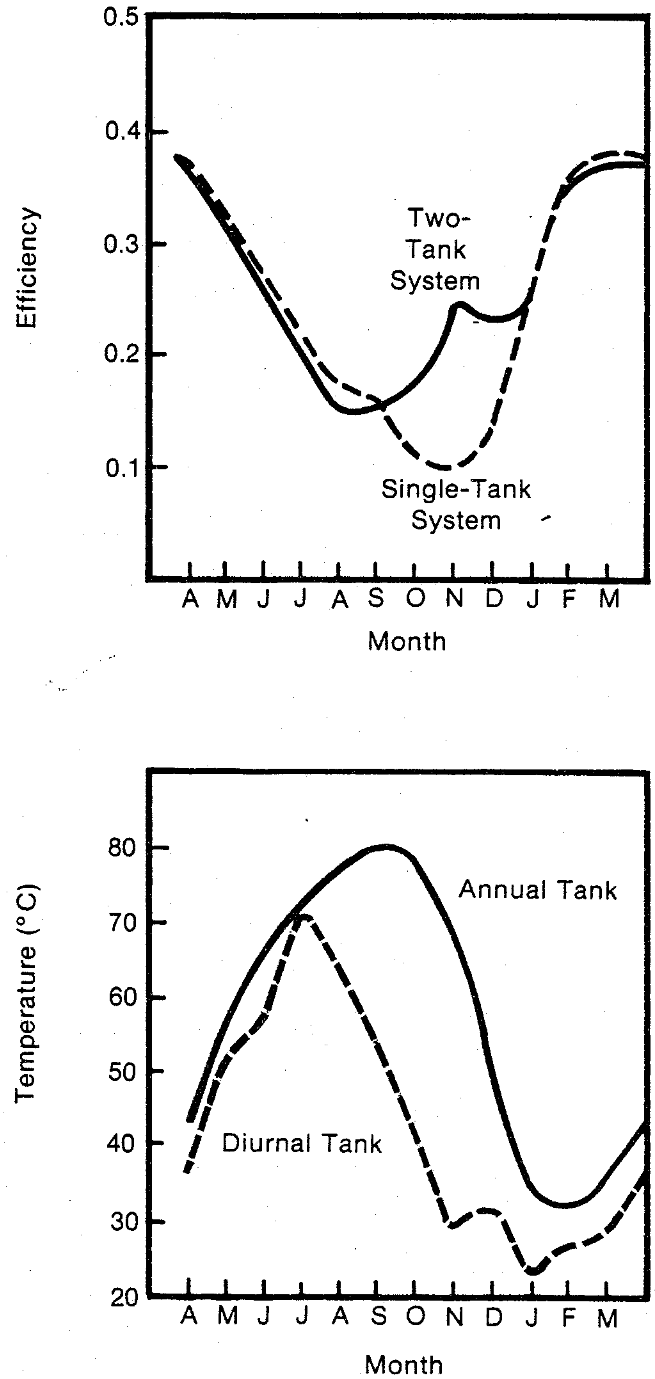


Figure 1-4. Monthly Efficiency and End-of-Month Storage Temperature for Two-Tank Annual Storage System
System is for flat-plate collector system, Boston, Mass., with standard load.

SECTION 2.0

METHOD OF STUDY

This study is based on a daily-step simulation described in a previous publication (Baylin and Sillman 1980). The basic assumptions of this model, including collector performance parameters, are presented in Appendix A. Selection of a simulation with daily steps enables systems with small- and intermediate-sized storage tanks to be included in the study.

System designs are compared for a number of different locations, collector type and tilt, building types, and building design. The following subsections describe the major design variables included in the study along with notes concerning the significance of each.

2.1 LOCATION

Four locations were selected: Boston, Mass.; Albuquerque, N. Mex.; Bismarck, N. Dak.; and Medford, Oreg. Boston was selected to typify the moderate, humid climate of the northeastern and midwestern United States. Albuquerque is representative of the sunbelt, the region of the United States that is most favorable to solar applications. Bismarck and Medford were selected to represent climates suitable for annual storage—Bismarck because of its severe winters and Medford because of its winter rainy season.

2.2 FLAT-PLATE VERSUS EVACUATED-TUBE COLLECTOR

The choice of collector type affects the performance of annual storage systems through its effect on collector efficiency. Evacuated-tube collector efficiency changes little as collector operating temperature changes, while flat-plate collectors show much greater swings in efficiency. This difference affects the choice between diurnal (daily) and annual storage in two ways. Evacuated-tube collectors permit greater collection of solar heat during winter when climatic conditions are worse, thus improving the performance of diurnal storage systems and lessening the need for annual storage. On the other hand, use of evacuated-tube collectors eases a major problem of annual storage systems: reduced collector efficiency due to higher operating temperatures.

2.3 COLLECTOR TILT

Two collector tilts are used, one equal to latitude and one equal to latitude plus 10 degrees. The sharper tilt favors solar collection in winter, while the less sharp tilt favors spring, summer, and fall collection. Collectors with the sharper tilt perform better for nearly all systems, while collectors with the less sharp tilt are most advantageous for systems with very large storage. Unless otherwise specified, system sizing and performance described in this study all have a collector tilt of latitude plus 10 degrees.

2.4 BUILDING TYPE

Four building configurations are modeled: single-family houses with a 50-unit district heating system, individual single-family houses, 10-unit apartment buildings with a

50-unit district heating system, and 200-unit apartment buildings. These configurations are referred to in this work by the abbreviations SUB 50, SUB 1, TUB 50, and HUB 200, respectively. Building types were selected to be consistent with a previous study (Baylin 1980a). The building type affects system performance by changing the ratio of space heat load to hot water load and also by changing the proportion of heat lost from storage.

2.5 NATURE OF BUILDING LOAD

Included are systems for space heating only, systems for hot water only, and combined space heat and hot water systems. For combined space heat and hot water systems, the ratio of space heat to hot water load is varied among the four building types.

2.6 BUILDING DESIGN AND EXTENT OF CONSERVATION

Three basic building types are included: standard construction, passive design, and superinsulated design. The space heat loads are calculated by using an algorithm for calculating day-to-day building loads (see Appendix B). Key parameters in describing the building load are (1) gross shell loss, (2) miscellaneous heat gain, and (3) passive heat gain. Tables B-1 and B-2 in Appendix B present these values along with final yearly loads for all building types.

The standard building loads are found by using the degree-day method, with a miscellaneous heat-gain equivalent of 1.5°C temperature difference. Miscellaneous heat typically provides 10% of the total yearly heat load in this instance. The passive designs include reduced gross shell load and passive gain designs in which miscellaneous heat provides 15%-20% of the gross shell load and passive solar heat provides 40%-50% of the gross shell load. The remainder is provided by the active system.* Superinsulated houses represent a relatively new building concept (Shurcliffe 1980). These are houses built for northern climates with very well-insulated walls [20-30 cm (8-12 in.)] and nearly airtight construction. Typically, miscellaneous heat provides a significant fraction of the gross shell load, which is already reduced far below that of a standard house by insulation. Designs used here had 35% of the gross shell load provided by miscellaneous heat and 35% by passive gain. Both passive and superinsulated designs are assumed for houses and small apartment buildings. High-performance passive systems for large buildings may be more limited than for small buildings, because of heat distribution problems. Consequently, only two designs are used for large apartments: a standard design and a conserving design in which miscellaneous heat and passive gain supply 30% and 25% of the gross shell load, respectively.

The variation in building design affects annual storage system performance in many ways: the shape of the annual load is changed; the pattern of day-to-day variations is changed, often to the detriment of the performance of active solar systems; and the relative sizes of the space heat and hot water loads are changed. The load sizes are of particular importance. In buildings of standard design, loads are equal; with superinsulated design, the hot water load is frequently greater.

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*In Albuquerque, N. Mex., passive design was found by simulation to meet over 80% of the building load. Superinsulated houses were not investigated for Albuquerque.

SECTION 3.0

RESULTS

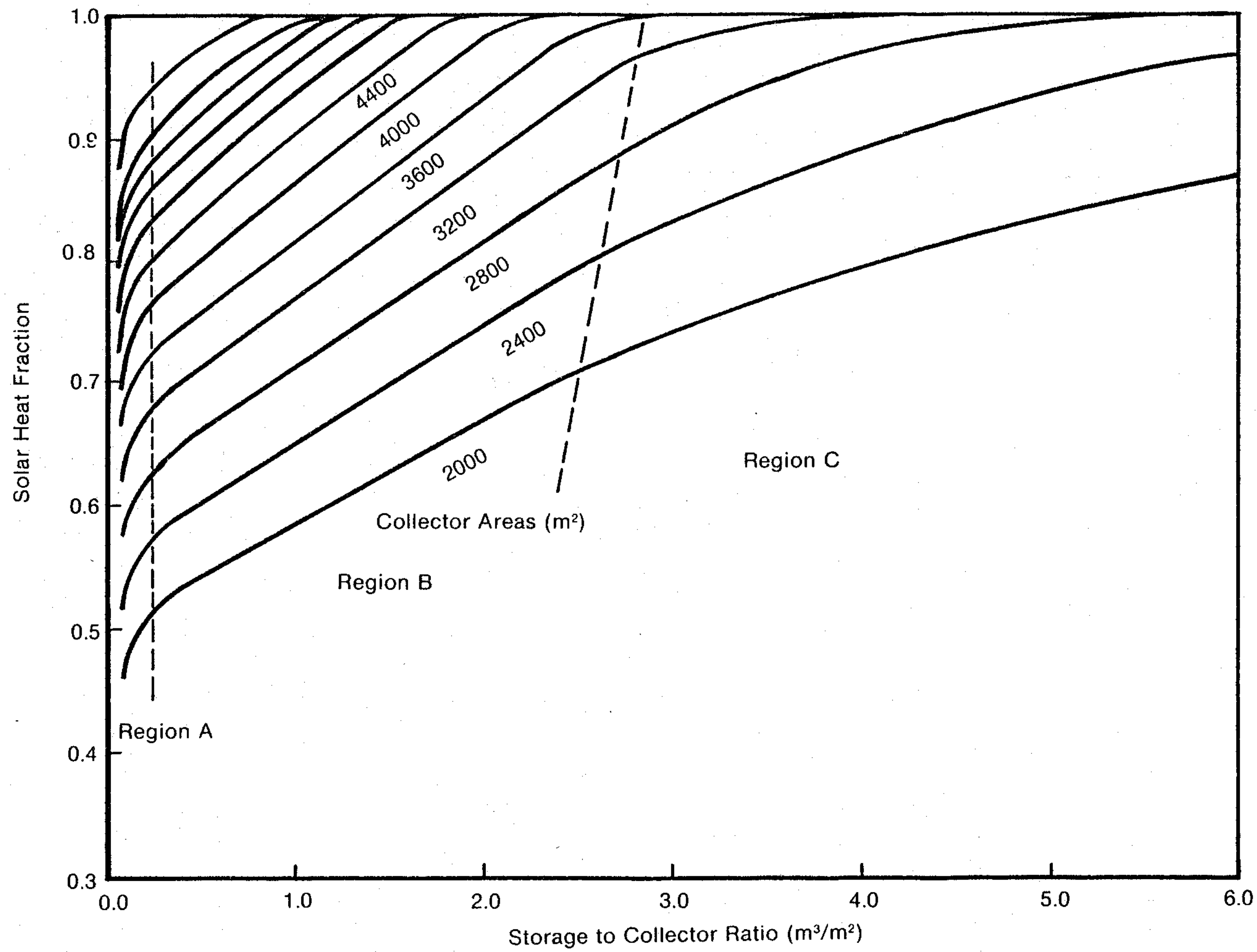
3.1 SYSTEM PERFORMANCE

The performance of solar heating systems with long-term storage may be evaluated in two ways. The first method is to examine system performance with varying storage size while collector area is held constant. A plot of performance versus storage size shows the performance gain attributable to long-term or annual storage. The second method is to plot the trade-off between collector and storage size while assuming system performance will remain constant. The trade-off plot is akin to the standard economic technique of plotting performance isoquants in a resource space. Taken together, the system performance and collector/storage trade-off plots provide a complete picture of sizing options for solar heating systems with long-term storage.

Figure 3-1 shows the performance and trade-off plots for a typical annual storage system. The patterns shown in Fig. 3-1 permit the identification of three regions with different performance characteristics: a diurnal and weekly storage region (Region A in the graphs), an intermediate region (Region B), and an annual storage region (Region C). In the diurnal storage region, the storage tank provides day-to-day or week-to-week storage, and the system performance curve slopes sharply upward. In the intermediate storage region, system performance improves steadily with storage size because the amount of heat stored from summer to winter increases. The upper bound of Region B represents annual storage at the point of "unconstrained operation" (Hooper and Cook 1980). At this point, storage is just large enough to store all heat collected during the summer months without exceeding its allowed maximum temperature. Larger storage tank sizes (Region C) would provide no extra storage capacity, although they do improve collector efficiency by lowering system operation temperatures. The pattern of the three regions is shown more clearly in Fig. 3-2, which plots the slopes of the performance and trade-off curves in Fig. 3-1. Figure 3-2 shows that the performance and trade-off curves vary linearly throughout the intermediate region, up to the point of unconstrained operation.

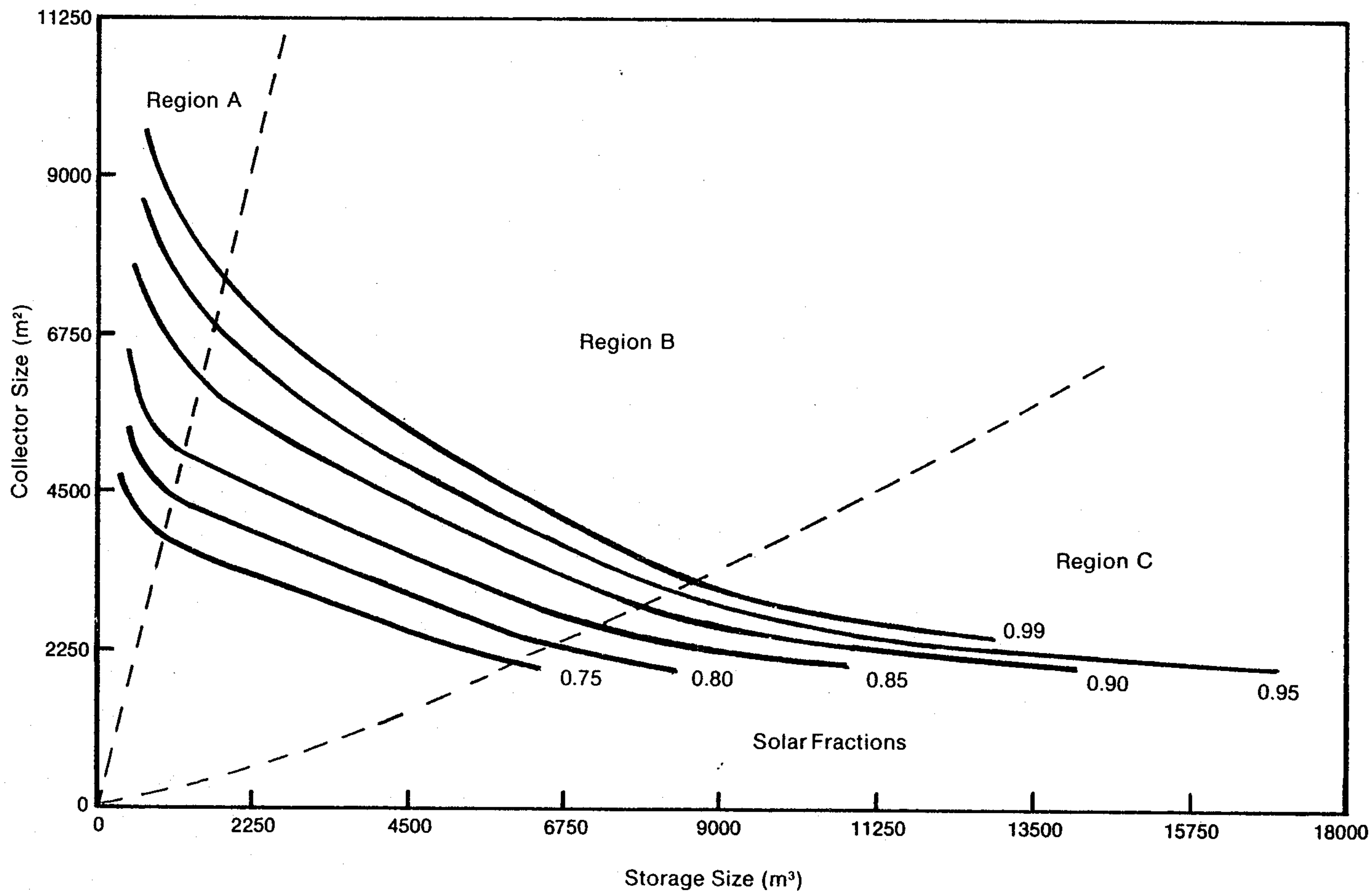
Because of the linear pattern of the performance and trade-off plots, the point of unconstrained operation is the only likely economic optimum. As illustrated in Fig. 3-3, the optimum will occur at either the lower or the upper bound of a region of linear system performance, but not at an intermediate point. In practice, intermediate optima can occur because the performance curves are not perfectly linear. These intermediate optima are rare, however, and represent at best a slight savings over diurnal or annual storage systems. It may be assumed that optimal systems will be either annual storage systems near the point of unconstrained operation or diurnal storage systems.

The same pattern is repeated for each system investigated in the study. The system performance and collector/storage trade-off plots, shown in Appendix C, all follow a linear pattern bounded by the points of unconstrained operation. Consequently, unconstrained systems represent the only possible long-term storage optima. Note, however, that unconstrained systems do not always have the large storage tank sizes that are commonly associated with the term "annual storage." A system that provides only space heat may have a storage-to-collector ratio as high as 5 m^3 to 1 m^2. A system that also provides a large hot water load may have a storage-to-collector ratio of 1 m^3 to 1 m^2 or less (buffer storage) and still be at the point of unconstrained operation. Such a pattern is illustrated in Fig. 3-4. These buffer storage systems are used when the need for



(a) System Performance

Figure 3-1. System Performance and Collector Storage Trade-Off Curves for a Typical Annual Storage System
System is for a Boston, Mass., SUB-50, standard space heat load, using flat-plate collectors. The dotted lines separate regions A, B, and C defined in the text.



(b) Collector-Storage Trade-Off

Figure 3-1. System Performance and Collector Storage Trade-Off Curves for a Typical Annual Storage System (Continued)

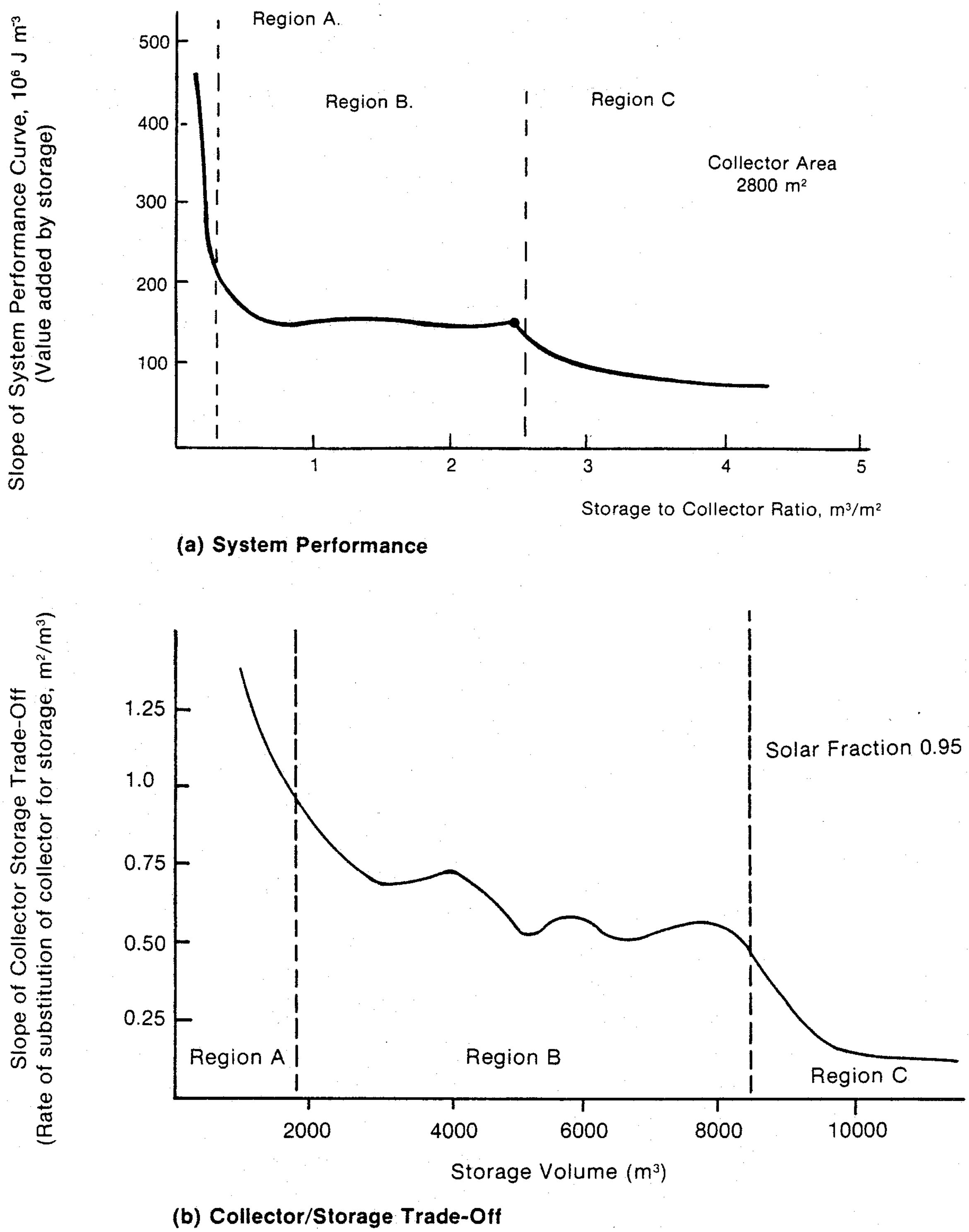


Figure 3-2. Slope of Performance and Trade-Off Plots in Figure 3-1
(Slope of Figure 3-1(a) has been converted to energy units.)

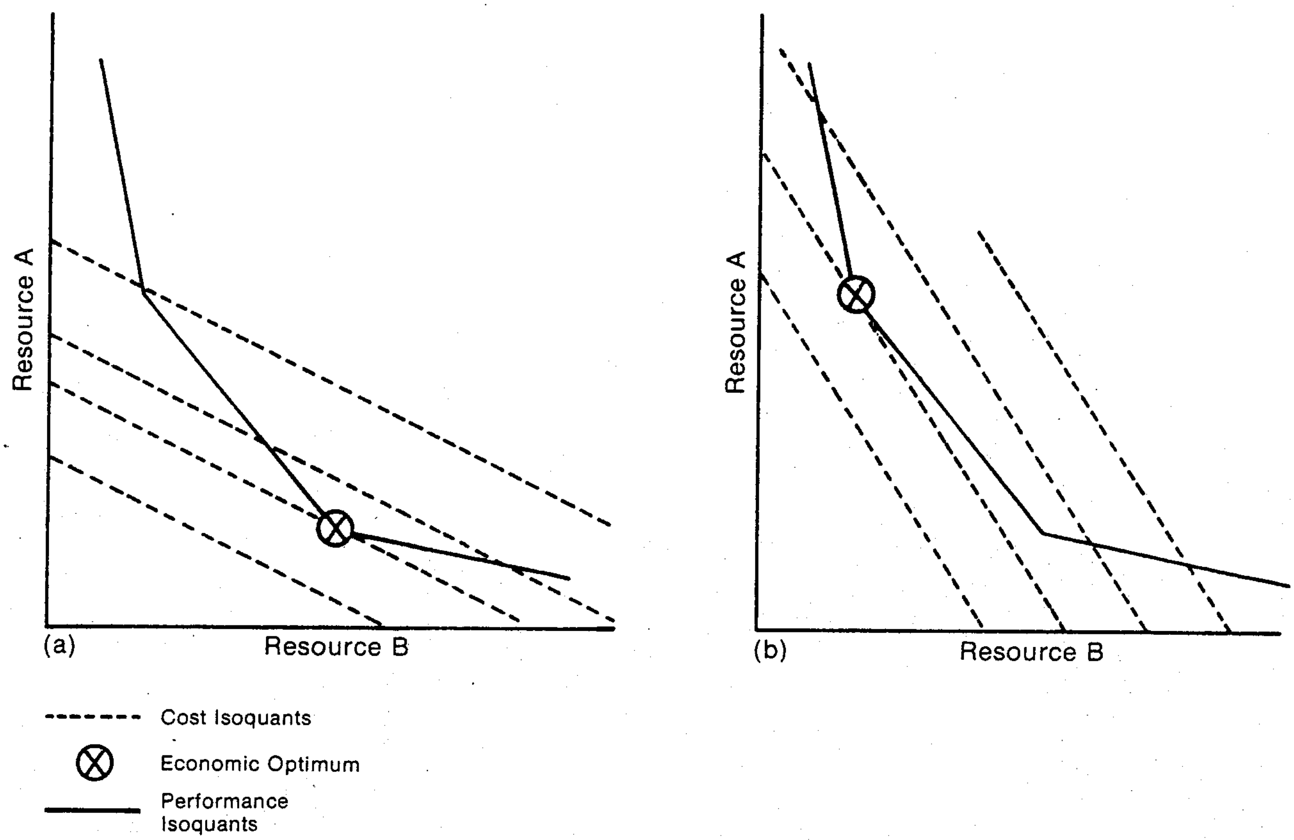


Figure 3-3. Economic Optima in a Region with Linear Design Trade-Offs
Plots (a) and (b) assume different unit costs for resources.

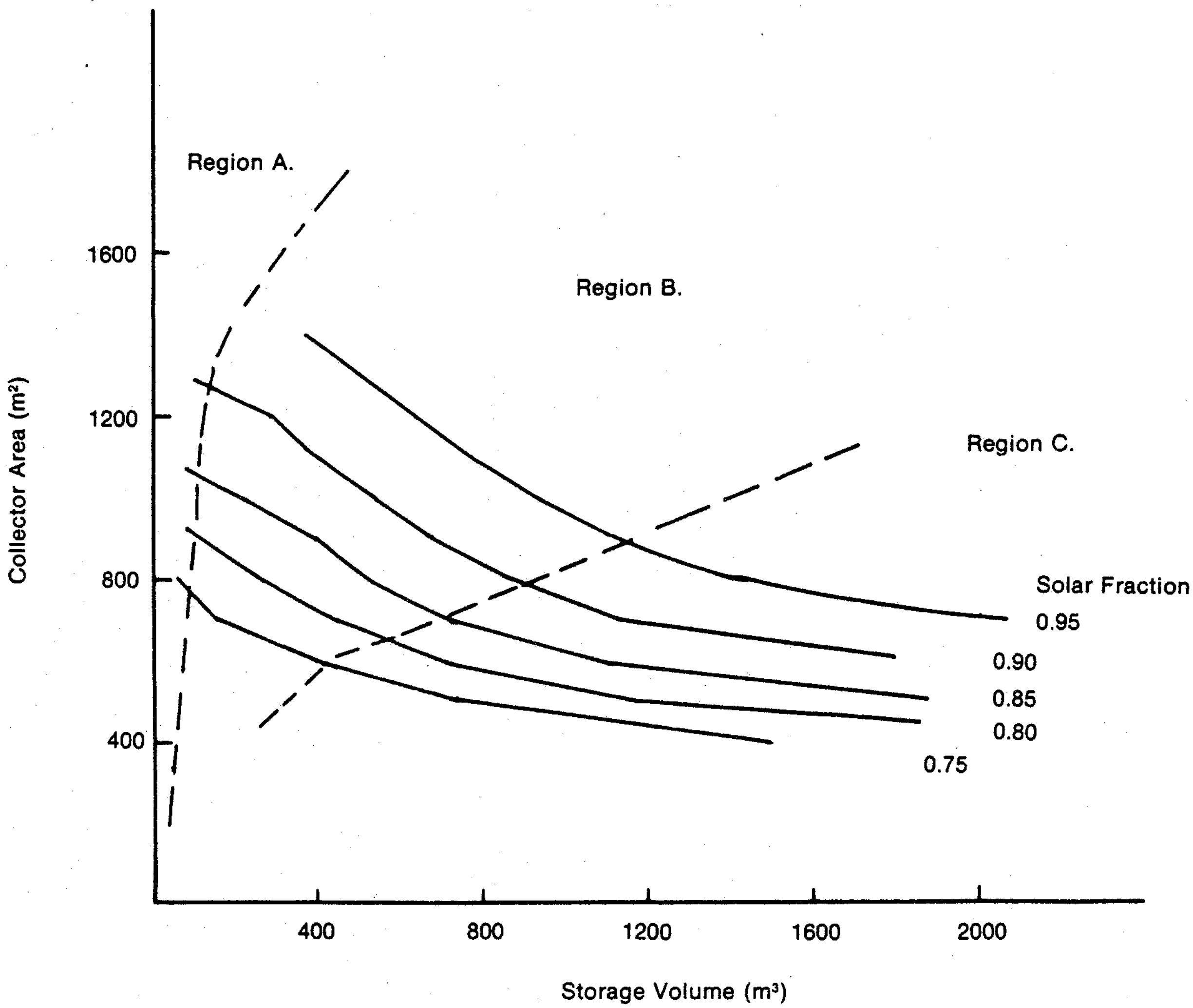


Figure 3-4. Performance of Annual Storage System with a Large Hot Water Load

System is a two-tank system with flat-plate collectors for Boston, Mass., with a SUB-50 superinsulated load. Hot water accounts for 60% of the annual load.

seasonally stored heat, as indicated by the summer-to-winter load variation, is relatively small. Although the amount of stored heat is less, these systems show the same operating characteristics (performance curves, month-to-month storage temperature, etc.) as do larger annual storage systems.

The conclusion that only unconstrained systems are worthy of consideration greatly simplifies the job of systems analysis. The key parameters for system evaluation are the slopes of the system performance and collector/storage trade-off curves. The slope of the system performance curve represents the increase in supplied energy resulting from an increase in storage size. This parameter will be referred to as the "net energy added by storage" and will be expressed in energy units per cubic meter. Theoretically, the net energy added by annual storage is at most equal to the amount of heat stored over the annual cycle. Based on a 48°C storage temperature swing over the annual cycle, the maximum net energy added is 200 MJ/m^3 per year. The net energy added by storage is used to determine whether annual storage is preferable to a system with smaller storage and greater reliance on backup power.

The slope of the collector/storage trade-off curve gives the rate at which collector size (in square meters) may substitute for storage (in cubic meters) if system performance is to remain the same. This trade-off parameter, expressed in m^2/m^3, is used to choose between annual storage and diurnal or weekly storage systems once a given level of system performance is specified. A large trade-off parameter means that a large collector size may be replaced by a given increase in storage. Consequently, a larger trade-off parameter favors annual storage systems over a diurnal or weekly storage system that provides the same solar fraction.

Appendix C presents complete results of the systems study. The tables in Appendix C give the following information for each system design:

- Collector and storage size for the point of unconstrained operation;
- Net energy added by storage and collector/storage trade-off, explained above;
- Solar fraction (i.e., the percentage of the total building load met by solar heat); and
- Diurnal solar fraction. This is the solar fraction of an identical system without annual storage, assuming the annual storage tank is replaced by a diurnal tank. The diurnal solar fraction indicates how significant the annual storage component is to the system.

3.2 NEAR-100% SOLAR SYSTEMS

In the preceding section, the concept of unconstrained operation was developed as a criterion for the optimal sizing of annual storage systems. This criterion may be used to size annual storage systems once the solar heat fraction is chosen. In this section, the choice of solar heating fraction will be examined in detail.

Active solar systems with diurnal storage typically show diminishing returns as the system size is increased to meet a large percentage of the load. Figure 3-5 shows how system efficiency* decreases for larger diurnal systems, for both space heat and hot

*System efficiency is defined as the annual amount of heat delivered to the load divided by the total yearly insolation incident on the collector surface.

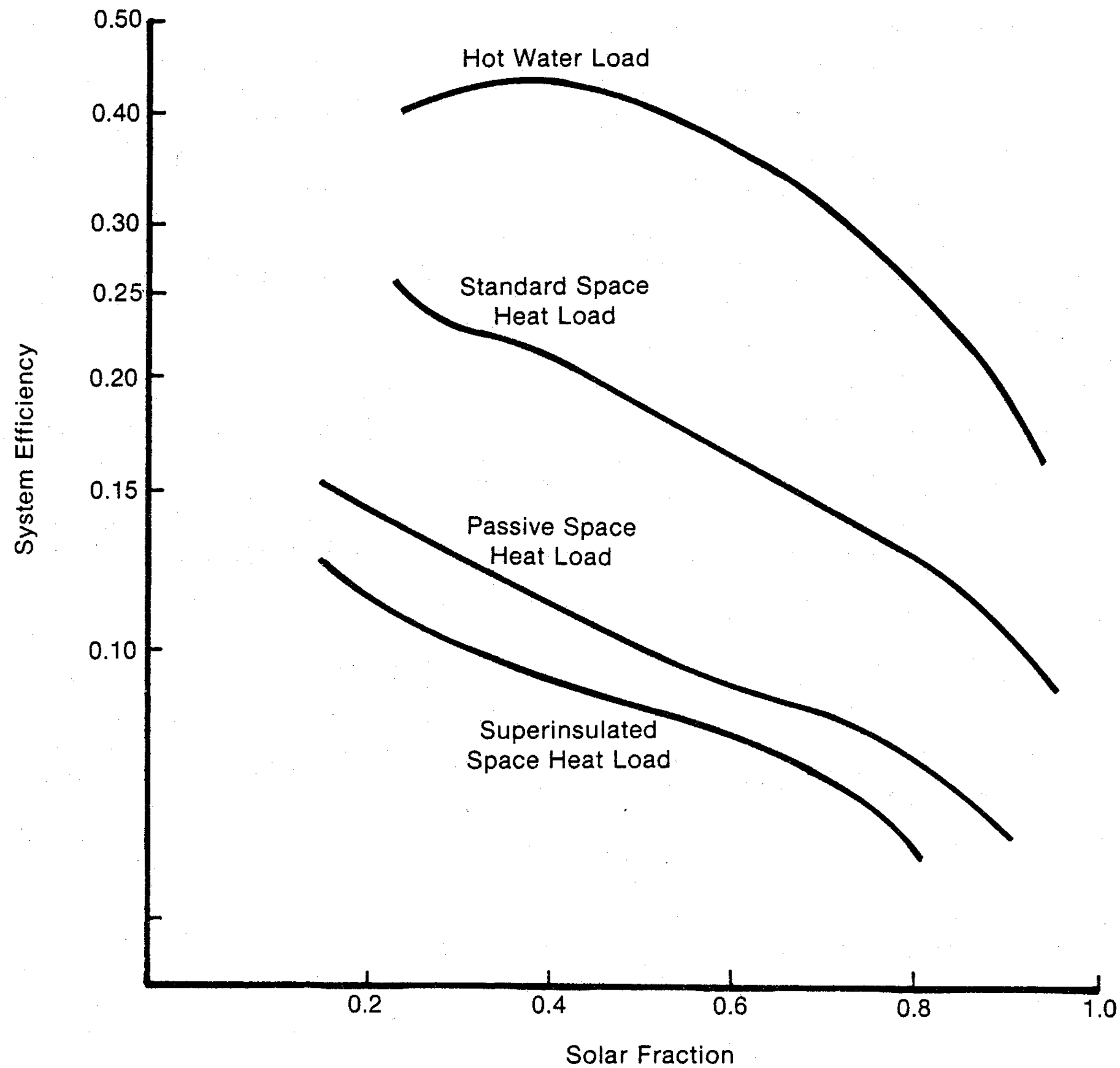


Figure 3-5. Efficiency of Diurnal Solar Systems vs. Solar Fraction
System for Boston, Mass., a SUB-50, flat-plate collector system.

water. As one approaches 100% solar heat, collector size increases and the collector stands idle for much of the time, especially in summer. Cost curves for diurnal systems typically pass through a clearly defined minimum at a solar fraction of 40%-70%. Furthermore, Fig. 3-5 shows that diurnal systems function poorly when added to an energy-conserving building.

Annual storage systems show much less of a tendency toward diminishing returns as the solar fraction is increased. Figure 3-6 shows the efficiency of unconstrained annual storage systems versus solar fraction for systems supplying space heat only. Returns are slightly diminishing when the solar fraction approaches 100%.

Figure 3-7 presents the same data in terms of cost. Cost figures are calculated as the sum of collector, storage, and fixed costs (Baylin et al. 1980b) for optimally sized diurnal and annual storage systems. The curves for diurnal storage systems show the standard pattern of a cost minimum at a solar fraction of 50%. When annual storage is considered, however, cost either decreases or remains constant as the solar fraction increases to 100%. The most cost-effective solar option would therefore be a system designed to meet 90%-100% of the load, not 40%-60% as is commonly assumed.

When an annual storage system provides hot water as well as space heat, there may be more of a tendency toward diminishing returns. Such systems typically must be large enough to provide 80% of the hot water load before any seasonal storage effect occurs. As shown in Fig. 3-8, small diurnal storage systems that provide predominantly hot water have a much higher efficiency than annual storage systems. As system size is increased, collector efficiency drops steadily until the collector field becomes large enough to permit annual storage. Efficiency then remains constant for all annual storage systems sized at the point of unconstrained operation.

Combined system cost is plotted against solar fraction in Fig. 3-9. The pattern shown is one of two economic optima, a diurnal storage optimum and a near-100% annual storage optimum. The component costs will determine which of these optima will be less expensive. For the prices assumed here, the annual storage-system energy cost is virtually equal to the optimal diurnal system cost. Consequently, a near-100% system will be the most cost-effective option whenever fuel costs are high enough to favor active solar heating.

The near-100% optima for annual storage systems shown in Figs. 3-7 and 3-9 are not accidental. Because annual storage systems show near-constant returns as solar fraction increases, near-100% systems are the likely optimum if annual storage is used at all. The design criteria for annual storage systems is now complete. Optimal systems will be those designed at the point of unconstrained operation and supplying a large percentage (90% or higher) of the given load. The remainder of this study will examine the performance and economics of annual storage systems in specific applications. Annual storage system sizes will all reflect these design criteria.

3.3 SPACE HEATING SYSTEMS

Systems designed for only space heating are much simpler than combined space and water heating systems. Although combined space and water systems are generally preferable, space heating systems have applications in commercial buildings that have zero or negligible hot water load.

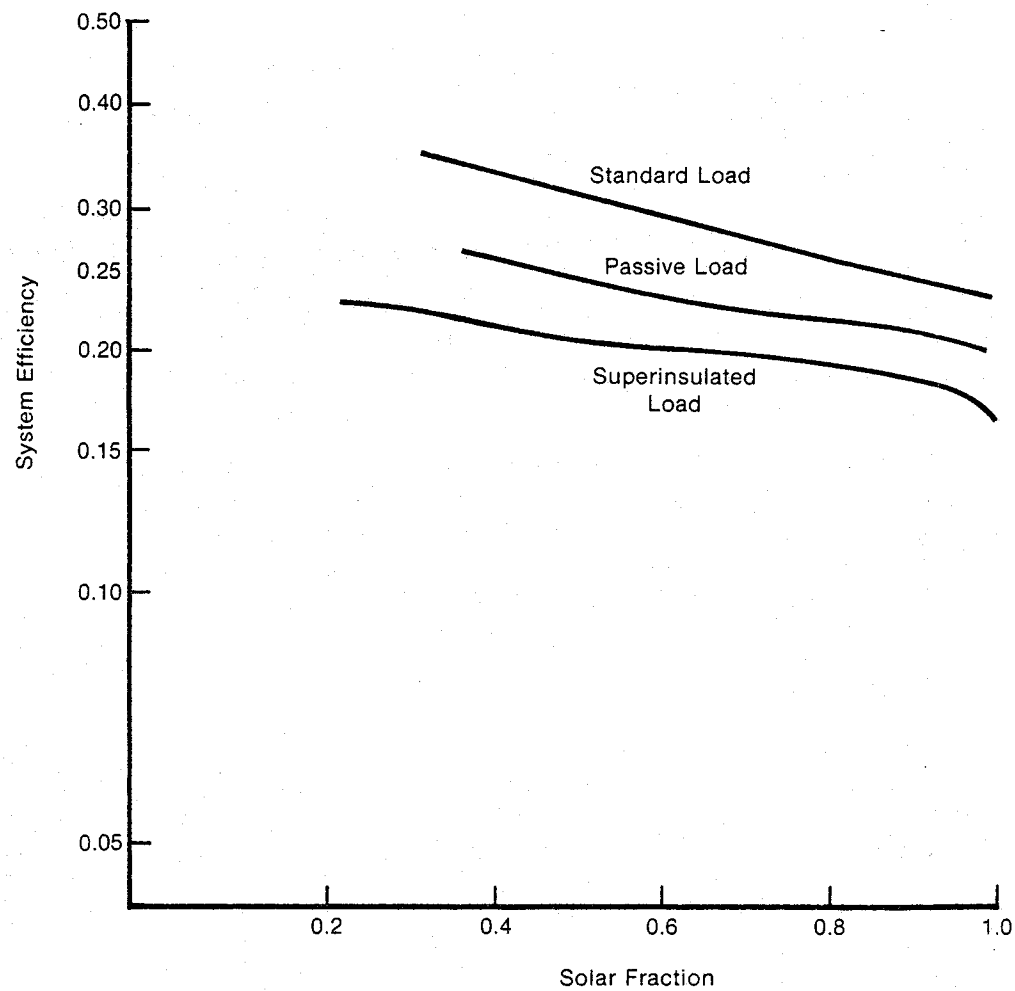


Figure 3-6. Efficiency vs. Solar Fraction for Annual Storage Systems (Space Heat Only)

Systems for Boston, Mass., SUB-50 with flat-plate collectors. All systems are sized near the point of unconstrained operation. Storage size is roughly proportional to collector size for these systems at a ratio of 3 m^3 : 1 m^2.

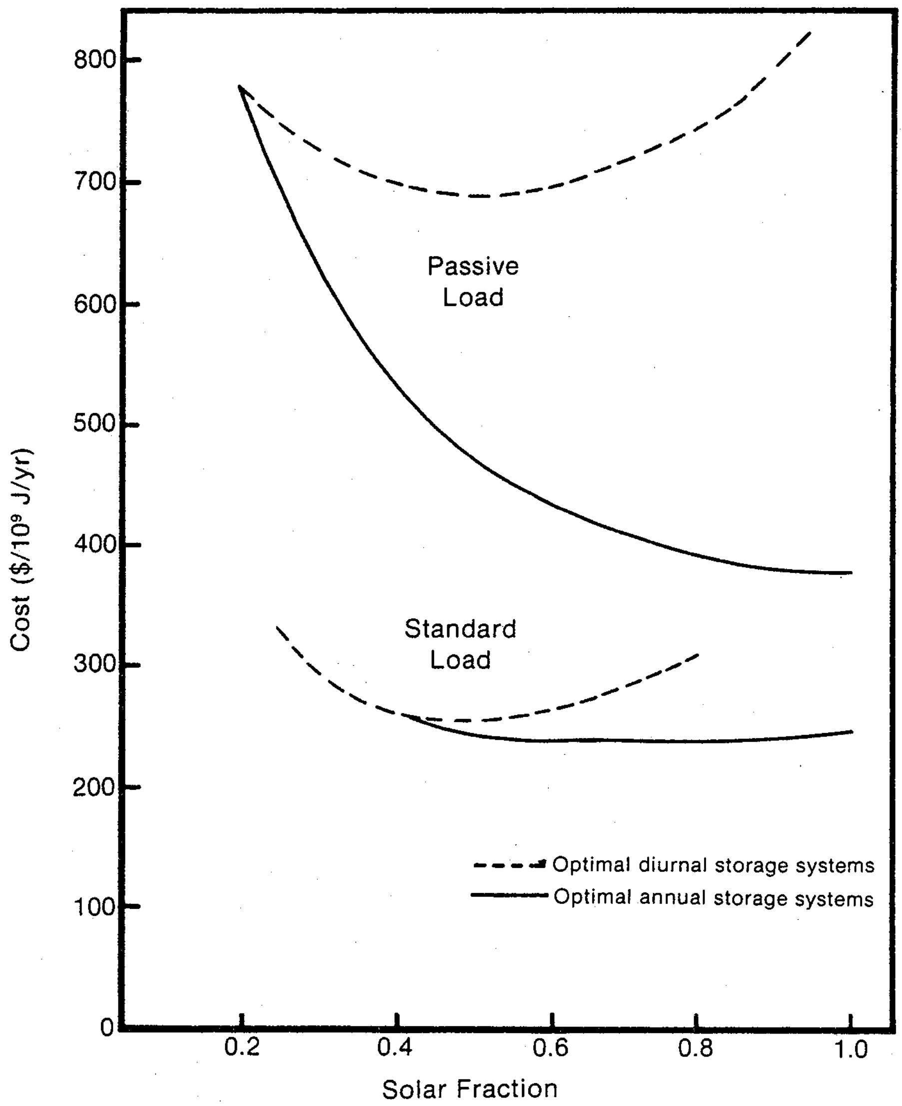


Figure 3-7. System Cost per Unit Heat Delivered vs. Solar Fraction for Space Heating Systems.

Systems are for Boston, Mass., with flat-plate collectors, for a 50-unit district of single-family houses. Cost is the sum of the collector cost at $140/m²; storage cost according to the equation $C_S = 385 \times [\mathrm{Vol}\ (m^3)]^{0.72}$; and the fixed cost. Fixed cost is set equal to $200,000 per standard, $120,000 for passive construction. All costs are in 1979 dollars.

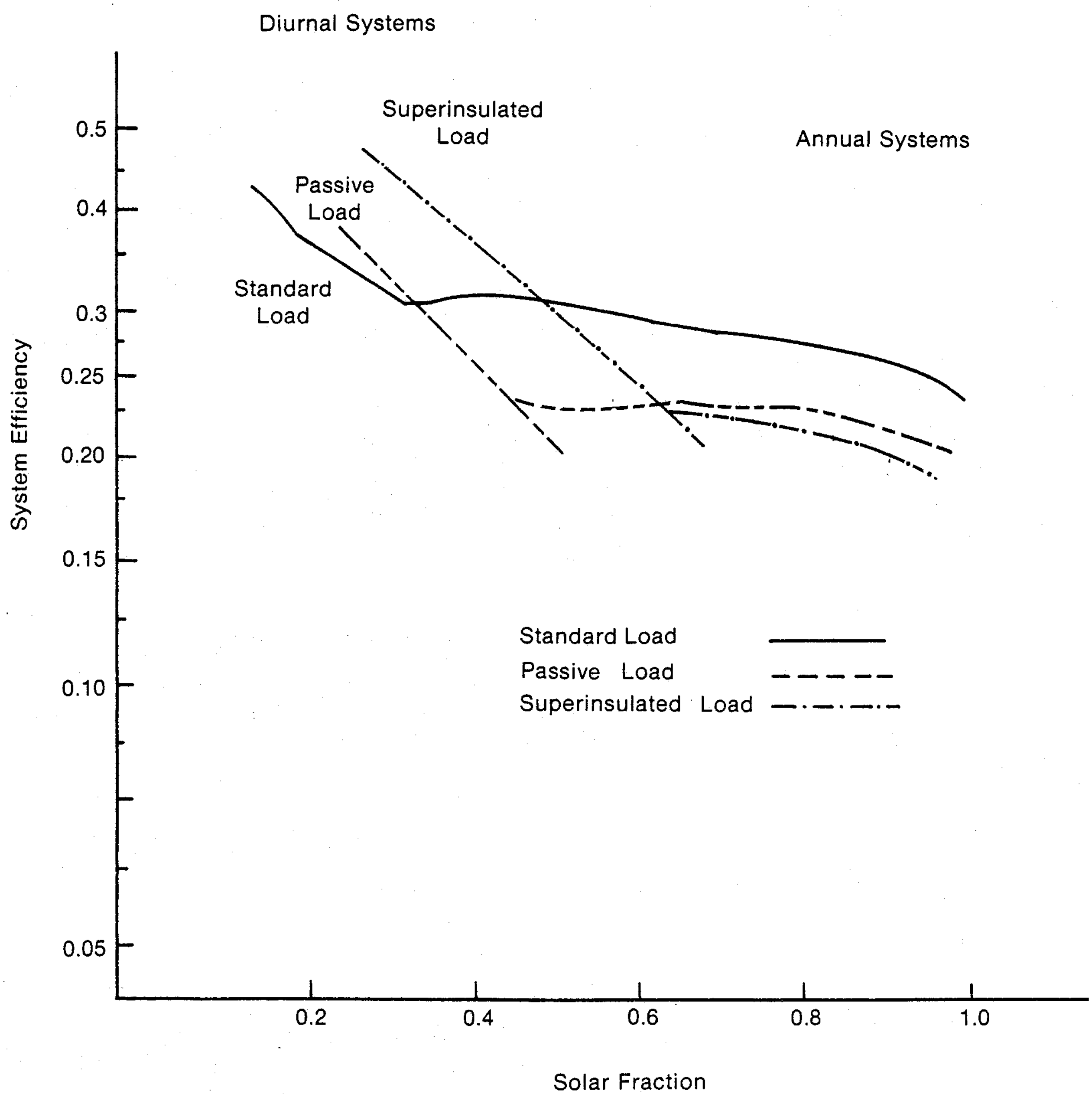


Figure 3-8. Efficiency vs. Solar Fraction for Combined Space Heat and Hot Water Loads
Annual storage systems are sized for the point of unconstrained operation. Annual storage size varies greatly, increasing at larger solar fractions. Diurnal storage systems are used when annual storage is not feasible. Systems are for standard, passive, and superinsulated SUB-50 loads, with flat-plate collectors, Boston, Mass.

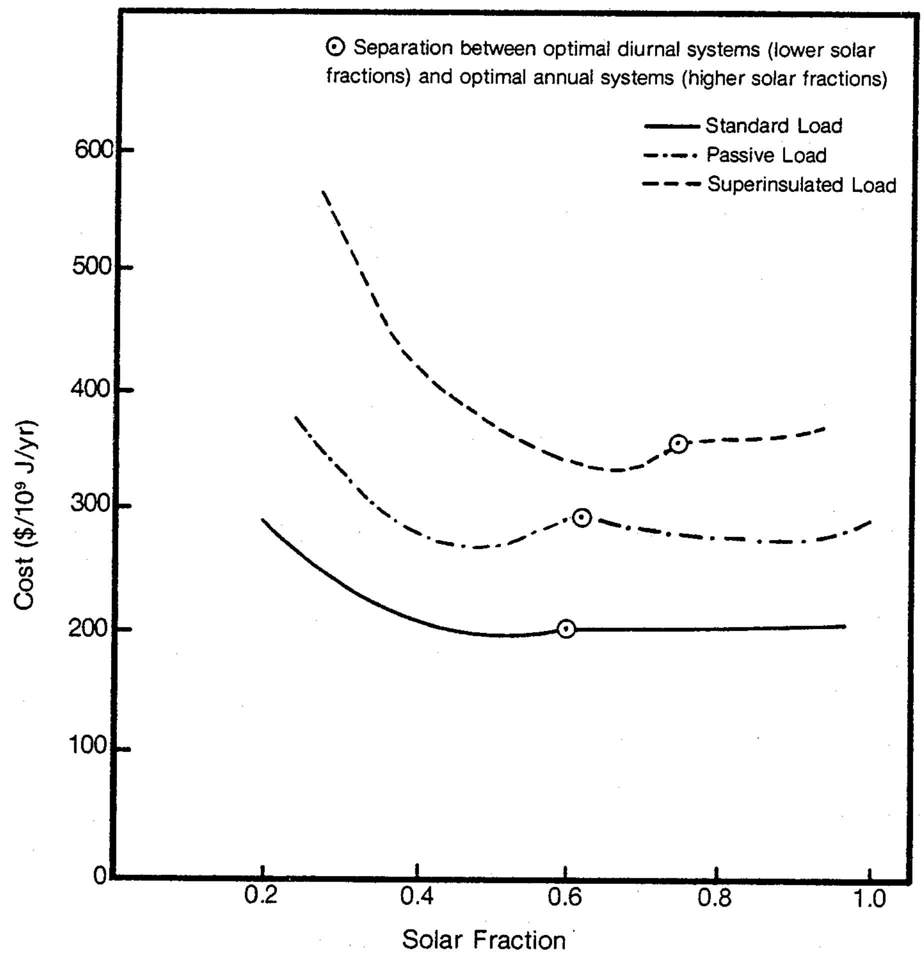


Figure 3-9. System Cost per Unit Heat Delivered vs. Solar Fraction for Combined Space Heat and Hot Water Systems

Systems are for Boston, Mass., SUB 50, with flat-plate collectors as in Figure 3-14. Cost is the sum of collector cost at $140/m^2$, storage cost according to the equation $C_s = 385 \times (\text{Vol. (m}^3))^{0.72}$, and the fixed cost. Fixed cost is set at $200,000 for standard, $150,000 for passive, and $120,000 for superinsulated construction. All costs are in 1979 dollars.

Space heating systems were analyzed for a 50-unit district of single-family houses including standard, passive, and superinsulated house designs. It is anticipated that building loads for apartments and commercial buildings are similar to the single-family house load and that annual storage systems would thus show similar characteristics. Complete results of simulations are presented in Appendix C.

3.3.1 Net Added Energy and Collector Type

When evacuated-tube collectors are used, the net energy added by storage is close to the theoretical maximum of 200 MJ/m^3. With flat-plate collectors, the net energy added by storage is significantly less. When a two-tank system is used with flat-plate collectors, the net added energy may be 150-180 MJ/m^3; with a single tank, the net energy is 130-160 MJ/m^3. The net added energy also shows greater variation among different locations and building types when flat-plate collectors are used.

The net added energy is affected most by the collector operating efficiency. As described in Sec. 1.0, collector efficiency tends to be lower in annual storage systems, as opposed to diurnal systems, during the fall and early winter months. When evacuated-tube collectors are used, this drop in efficiency is slight and net added energy remains high. With flat-plate collectors, particularly in single-tank systems, collector efficiency is more sensitive to the collector operating temperature and the efficiency drops sharply in fall and early winter. This loss in efficiency is enough to lower the net energy added by storage.

3.3.2 Standard, Passive, and Superinsulated Construction

Passive and conserving building designs have two major characteristics that affect the design of an active solar system for backup heat. First, the annual shape of the passive and superinsulated building load is different from the load of a standard building. Passive buildings rarely need additional heat during spring and fall and, consequently, their yearly load occurs within three or four months. A standard building design requires heat in all but the summer months (see Fig. 3-10). A second difference is that day-to-day variations in load are relatively small for a standard building, reflecting only day-to-day changes in temperature. For a passive or superinsulated building, however, the day-to-day load is much more sporadic with no heat required on sunny days even in the middle of winter.

The effect of building design is greatest for diurnal systems. As shown in Sec. 3-2, diurnal system efficiency drops when used with a passive or conserving building load. The poor performance of diurnal systems may be due either to the yearly load shape or to the greater day-to-day and week-to-week variations in load. The yearly load shape causes the solar collectors to be idle for a large part of the year. The daily load variation hampers system operation because maximum solar collection occurs precisely on those days when there is no load for a passive house. Further investigation shows that the monthly performance as well as the yearly performance of diurnal systems is poor. This indicates that the daily and weekly load variation is a primary cause of poor diurnal performance with passive loads, although the uneven yearly load pattern is also a major influence.

Figure 3-11 compares system performance with storage size for the three different building designs. The figure shows that performance drops much more sharply at small storage sizes for a conserving load. This indicates that even a diurnal system requires larger storage when used with a passive or conserving load. Furthermore, the

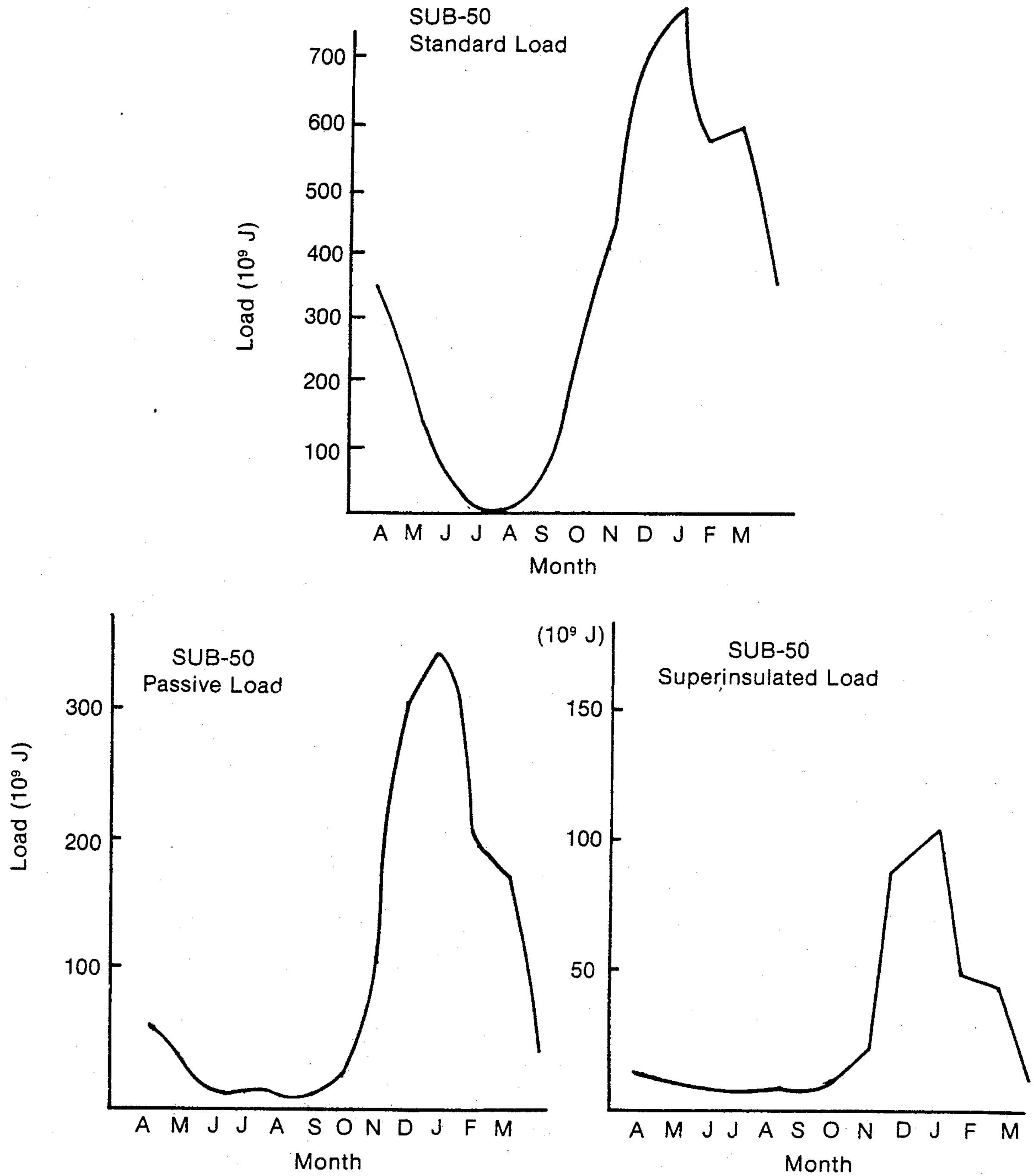


Figure 3-10. Monthly Load for Different Building Designs
(Boston, Mass.)

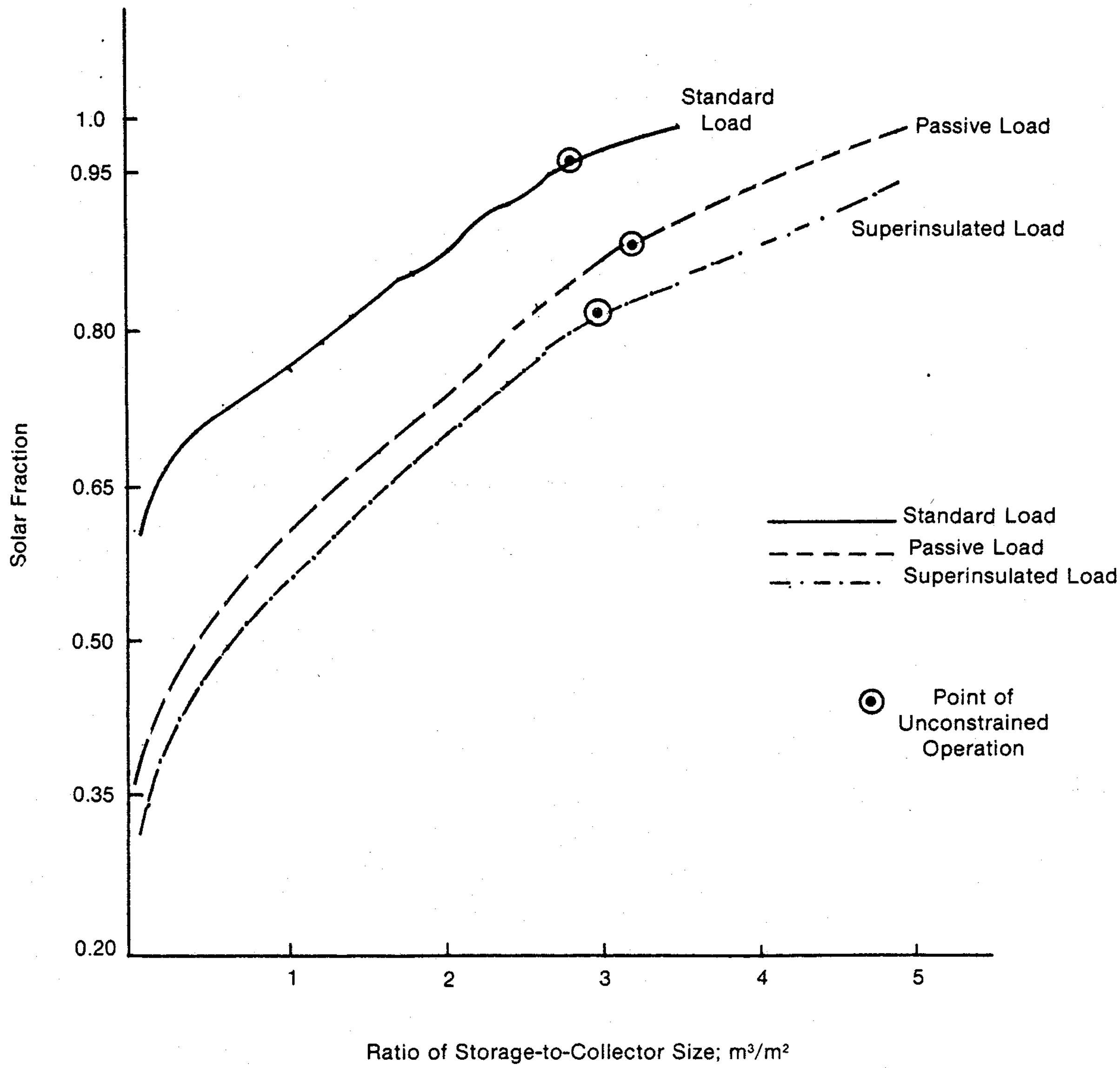


Figure 3-11. Performance of Annual Storage with Standard, Passive, and Superinsulated Loads

Systems are SUB-50, space heat only; with flat-plate collectors, in Boston, Mass. Collector size is the same relative to annual load for the three systems.

performance curve with a passive load continues to slope more steeply than the standard system curve for intermediate-size storage. The steeper slope indicates that week-to-week storage may be important for passive load systems.

Because annual storage is large enough to dampen out daily and weekly load variations, the type of building load has a much smaller effect on annual storage systems. Typically, the efficiency of annual storage systems is 15%-20% lower with a passive building load than with a standard load, and 20%-30% lower for a superinsulated load. This drop in efficiency is due to the annual load shape. Since the passive load is concentrated in the winter, yearly storage temperatures must be higher to achieve the same solar fraction as a system with a standard load. The drop in efficiency is significantly smaller when evacuated-tube collectors are used. Because of the more concentrated annual load pattern, systems also require a larger storage tank in proportion to collector area when used with a passive or superinsulated load.

Use of passive or superinsulated construction can cause the net energy added by storage to either increase or decrease. The net added energy may increase with passive buildings because storage serves more of a dual purpose, combining daily and weekly with annual storage. On the other hand, the average operating temperature tends to be higher for systems with passive building loads, which causes poorer system performance.

The trade-off parameter is nearly always larger for passive or superinsulated buildings than for standard buildings. This is the result of increasingly poor performance of diurnal and intermediate storage systems at high solar fractions. It often happens that the net added energy is lower for passive buildings (favoring diurnal systems), but the trade-off parameter is also larger (favoring annual systems). This type of pattern occurs because active systems, with or without annual storage, perform more poorly with passive construction.

Results of the analysis for systems in Boston are typical. Seasonal storage systems have a ratio of storage-to-collector size (m^3:m^2) of 3:1 with standard construction and 4:1 with passive or superinsulated construction. The same collector array without seasonal storage would provide 60%-66% of the space heat load with standard construction and 42%-50% with passive or superinsulated construction. The trade-off parameter ranges from 0.7 to 1.0 m^2/m^3 for passive loads and from 0.45 to 0.70 m^2/m^3 for standard loads. The net energy added storage remains uniform for standard, passive, and superinsulated houses at a fairly high level: 160-210 MJ/m^3 (near the theoretical maximum) for evacuated-tube systems and two-tank, flat-plate systems and 140-160 MJ/m^3 for single-tank, flat-plate collector systems.

3.3.3 Performance Variation by Location

The performance characteristics of space heating systems show some variation among the four locations. The net energy added by storage is significantly higher in Medford, reaching 200 MJ/m^3 even for flat-plate collector systems, and is slightly less in Bismarck. The cause of this variation is the climatic pattern in the fall and early winter. As previously noted, the use of annual storage results in a reduction in the winter collection efficiency, and the reduced solar collection counts against the net energy added by storage. In Medford, winter insolation is so small that the poor collector efficiency is insignificant. In Bismarck, by contrast, winter insolation is high and reduced efficiency more important.

The trade-off parameter is similar for the three northern cities, indicating that optimization of collector versus storage size is similar. In Albuquerque the trade-off parameter was much smaller, with a value of 0.2 m^2/m^3. This is due to the greater insolation in Albuquerque, which causes the collector to weigh heavier in the trade-off with storage.

The major difference in system design among the four cities was the system size, which was found to be very similar between Boston and Bismarck; storage to collector ratios were the same, and system performance without seasonal storage was equivalent. This apparently reflects the similar climatic pattern of Boston and Bismarck (eastern humid continental climate), despite the fact that Bismarck's winter is much more severe. By contrast, the storage component was much larger in Medford. The equivalent system without annual storage in Medford would yield a solar fraction of only 52%-58% for standard construction and only 25%-30% for superinsulated construction. This is much smaller than the corresponding value for Boston given in Sec. 3.3.2. The storage-to-collector ratio is correspondingly larger in Medford. In Albuquerque, seasonal storage was a smaller component than in the other cities, with daily systems yielding 65%-72%. The storage to collector ratio in Albuquerque was large (4-6 m^3/m^2), again a reflection of increased insolation in Albuquerque. Annual storage appears to be most useful in locations with sunny summers and unusually cloudy winters (Medford), rather than in places with unusually cold winters (Bismarck).

3.4 HOT WATER SYSTEMS

Seasonal storage tends to have very little usefulness in systems designed to provide hot water only, primarily because of the nonseasonal nature of the hot water load. Although insolation does vary throughout the year, the gain achieved by storing summer heat for use in winter is more than offset by the loss in efficiency with seasonal storage systems.

A further important factor concerns the nature of hot water systems. The space heat load can be met with heat collected at any temperature above 30°C, but meeting the entire hot water load requires collecting heat at 55°C or more. Low-temperature solar heat can be used as a hot water preheat. This type of system yields sharply diminishing returns as the system size is increased to meet a large percentage of the hot water load. It also provides a natural mechanism for matching load with available energy; a hot water system may provide substantially preheated water in winter and fully heated hot water in summer with the collection of extra heat for seasonal storage.

The slow reaction time of a seasonal storage tank further encumbers a hot water system. When a seasonal storage tank is fully discharged in winter, it may be at a temperature to provide only 50% of the hot water load. With a daily storage system, the tank would heat to 50° or 60°C on sunny days and provide nearly 100% of the hot water load. The seasonal storage tank would remain at 30°C and continue to provide only 50% of the load. This behavior becomes a serious drawback in seasonal storage systems designed to meet a large fraction of the load. It also causes the efficiency of hot water systems with annual storage to be much lower than those with diurnal storage.

For these reasons, seasonal storage typically provides zero yield for hot water systems with a single tank. Use of two diurnal storage tanks alone is found to increase performance by 10%. A two-tank system with seasonal storage does yield some further benefit because the small tank permits both collection and use of low-temperature solar heat in fall and the collection of high-temperature solar heat for hot water in the spring. The net energy added by annual storage is only 70-80 MJ/m^3, and it provides at most a 10% improvement in energy yield over diurnal two-tank systems. The storage-to-collection ratio is rarely higher than 1 m^3 to 1 m^2.*

3.5 COMBINED HEATING AND HOT WATER SYSTEMS

Combined systems are more complicated than either space heat or hot water systems. The performance of a combined system is influenced both by properties of space heat systems, in which seasonal storage has an almost constant value, and hot water systems, in which seasonal storage has low value and decreases system efficiency. The most important factors in the performance of a combined system are the sizes of the space heat and hot water loads relative to each other.

Combined systems may be analyzed as though they are two separate systems, one for space heat and one for hot water. Table 3-1 compares combined systems with systems for space heat only. Assuming both systems are annual storage systems designed at the point of unconstrained operation and both systems provide the same percentage of solar space heat, they will have the same storage size. In addition, the difference in collector size between the two systems compares consistently to the collector size of a solar hot water system that would meet the same fraction of the hot water load as does the combined system. Typically, the added collector area in the combined system is greater than the size of the equivalent hot water system by about 10%. This difference reflects the loss in efficiency that occurs when an annual storage system is used to provide hot water. With a two-tank system, the extra collector area in the combined system may be either greater or smaller than the size of the equivalent two-tank hot water system. System performance is significantly worse for combined systems in which the hot water load exceeds the space heat load.

Two-tank systems, initially investigated for space heating (Cha et al. 1979), appear to be most useful for combined systems with a large hot water load. For reasons discussed in the previous section, single-tank annual storage systems tend to perform poorly in meeting a hot water load. A two-tank system serves a dual purpose here. First, it permits the collection of low-temperature heat during November and December. Second, it may be used to collect high-temperature heat for hot water in March and April when the annual storage tank temperature is too low to provide hot water. This dual-purpose, two-tank system enables an annual storage system to provide both hot water and space heat efficiently.

The net added energy and the trade-off parameter for combined systems may also be compared to that of space heat systems. The net added energy and the trade-off parameter are the same for two-tank systems as for the equivalent space heat system. For single-tank systems, the net added energy is lower by 10%-25% when compared to space heating systems. The drop in the net added energy is greater when space heat loads are

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*These conclusions are based on the assumption that the daily hot water load remains constant throughout the year. There is evidence (Mixon 1976) that daily hot water loads are actually twice as great in winter as in summer. In that case, conclusions would be more favorable to annual storage systems. The net energy added by storage would rise to 90-100 MJ/m^3 in Boston and 120-140 MJ/m^3 in Medford. The net added energy in a combined system (see Section 3.5) would be similarly enhanced.

Table 3-1. COMPARISON OF SPACE-HEATING, HOT-WATER, AND COMBINED SYSTEM PERFORMANCE

All systems are for Boston, Mass., and use flat-plate collectors. Annual storage systems are all at the point of unconstrained operation. In two-tank systems, the second tank is sized by:

$$V_s\,(m^3) = 0.075\,A_c\,(m^2)$$

SYSTEM	COLLECTOR SIZE (m^2)	STORAGE SIZE (m^3)	SPACE HEAT FRACTION*	HOT WATER FRACTION*	EFFICIENCY
Standard construction, single-tank system					
Combined system	2800	5600	0.77	0.75	0.259
Space heat system	2270	5900	0.77	0	0.266
Hot water system	480	36	0	0.75	0.274
Combined system	3200	7040	0.85	0.77	0.249
Space heat system	2600	7050	0.85	0	0.254
Hot water system	520	39	0	0.77	0.260
Combined system	3600	7920	0.91	0.80	0.235
Space heat system	2900	8100	0.91	0	0.244
Hot water system	580	44	0	0.80	0.242
Combined system	4000	9600	0.98	0.83	0.226
Space heat system	3350	9400	0.98	0	0.226
Hot water system	650	49	0	0.83	0.224
Passive construction, single-tank system					
Combined system	1400	2000	0.70	0.78	0.215
Space heat system	760	2200	0.70	0	0.226
Hot water system	520	39	0	0.78	0.254
Combined system	1600	2900	0.83	0.81	0.211
Space heat system	910	3000	0.83	0	0.222
Hot water system	575	43	0	0.81	0.236

Table 3-1. COMPARISON OF SPACE-HEATING, HOT-WATER, AND COMBINED SYSTEM PERFORMANCE (Continued)

SYSTEM	COLLECTOR SIZE (m^2)	STORAGE SIZE (m^3)	SPACE HEAT FRACTION*	HOT WATER FRACTION*	EFFICIENCY
Passive construction, single-tank system					
Combined system	1800	3600	0.93	0.83	0.203
Space heat system	1040	3600	0.93	0	0.218
Hot water system	625	47	0	0.83	0.224
Combined system	2000	4000	0.98	0.85	0.191
Space heat system	1150	4000	0.98	0	0.210
Hot water system	670	50	0	0.85	0.212
Superinsulated construction, single-tank system					
Combined system	700	600	0.75	0.82	0.198
Space heat system	250	700	0.75	0	0.193
Hot water system	390	30	0	0.82	0.230
Combined system	800	800	0.85	0.84	0.184
Space heat system	300	840	0.85	0	0.183
Hot water system	420	31	0	0.84	0.218
Standard construction, two-tank system					
Combined system	2800	5600	0.79	0.86	0.274
Space heat system	2200	5500	0.79	0	0.279
Hot water (single-tank)	735	55	0	0.86	0.205
Hot water (two-tank)	600	45	0	0.86	0.250
Combined system	3200	7050	0.89	0.89	0.265
Space heat system	2600	7000	0.89	0	0.268
Hot water (single-tank)	830	62	0	0.89	0.188
Hot water (two-tank)	700	53	0	0.89	0.22
Combined system	3600	7920	0.96	0.92	0.252
Space heat system	2900	8400	0.96	0	0.256
Hot water (two-tank)	800	60	0	0.92	0.20

Table 3-1. COMPARISON OF SPACE-HEATING, HOT-WATER, AND COMBINED SYSTEM PERFORMANCE (Concluded)

SYSTEM	COLLECTOR SIZE (m^2)	STORAGE SIZE (m^3)	SPACE HEAT FRACTION*	HOT WATER FRACTION*	EFFICIENCY
Passive construction, two-tank system					
Combined system	1600	2880	0.84	0.91	0.224
Space heat system	960	3000	0.84	0	0.228
Hot water (two-tank)	750	56	0	0.91	0.204
Combined system	1800	3600	0.94	0.94	0.217
Space heat system	1020	3600	0.94	0	0.224
Hot water (two-tank)	860	64	0	0.94	0.190
Superinsulated construction, two-tank system					
Combined system	600	600	0.63	0.85	0.226
Space heat system	200	520	0.63	0	0.202
Hot water (two-tank)	360	24	0	0.85	0.257
Combined system	700	700	0.75	0.90	0.209
Space heat system	240	680	0.75	0	0.201
Hot water system	410	30	0	0.90	0.204
Combined system	800	960	0.90	0.926	0.199
Space heat system	320	900	0.90		0.182
Hot water (two-tank)	550	41	0	0.926	0.182

*Space heat fraction and hot water fraction refer to the percentage of the space heat and hot water loads, respectively, that are met by the solar heating system.

small and hot water accounts for a larger percentage of the total load. For superinsulated houses in which the hot water load is double the size of the space heating load or greater, the net added energy drops as much as 50% for a combined system when compared to a space heating system. This drop in the net energy occurs because the loss in efficiency of the hot water component is proportionately greater, while the amount of heat gained by the annual storage system becomes proportionately less. This effect is the same regardless of collector type. Because of this low net energy, two-tank systems are particularly useful for buildings with a larger load for hot water than for space heat.

Although a combined system offers no engineering advantage, it may offer a substantial economic advantage through the use of auxiliary equipment (piping, controls, etc.) that services both the space heat and hot water loads. Lovins (U.S. Congress 1978) has argued that the hot water component of a combined system may be used to justify the cost of auxiliary equipment that otherwise would make a space heat system prohibitively expensive for small building loads.

3.6 SINGLE-UNIT SYSTEMS

Annual storage systems for an individual single-family residence (SUB 1) are of interest because a number of innovative systems of this type have been built in recent years. (Esbensen and Korsgaard 1977; Besant et al. 1978). The major problem with single-unit systems is storage loss: while a 50-unit annual storage system may have a storage efficiency of over 90%, a single-unit system such as the Lyngby house (Esbensen et al. 1977) may have a year-round storage efficiency of 60% or less.

Single-unit system simulations were performed, assuming the same level of storage-tank insulation (0.11 $W/m^2{}^\circ C$) as assumed for 50-unit systems. Results show that the overall system efficiency for a single-unit system is 20%-30% lower than for the equivalent 50-unit system. The net added energy drops by 30%-50%. These results suggest that annual storage works much better for 50-unit districts than for individual houses. This is particularly true in light of economies of scale available in obtaining large storage tanks (Baylin et al. 1980b).

3.7 EFFECT OF COLLECTOR TILT

The two collector tilts used—tilt equal to latitude and tilt equal to latitude plus 10 degrees—result in slightly different performances. In general, the sharper tilt permits greater collection in winter at the expense of collection in the spring, summer, and fall. The sharp tilt is advantageous when storage is small. The shallower tilt increases summertime collection and thus makes use of larger annual storage tanks advantageous. When collector tilt is shallower, the point of unconstrained operation will occur at a larger storage size.

Figure 3-12 illustrates the difference in performance brought about by the different collector tilts. The sharper tilt is definitely favored when storage is small, and the shallower tilt is favored when storage is very large. The crossover point is typically near the point of unconstrained operation. Because the crossover point occurs most often in Region C, the sharper tilt is more likely to be economically optimal. However, the shallower tilt permits greater performance for a collector of given size.

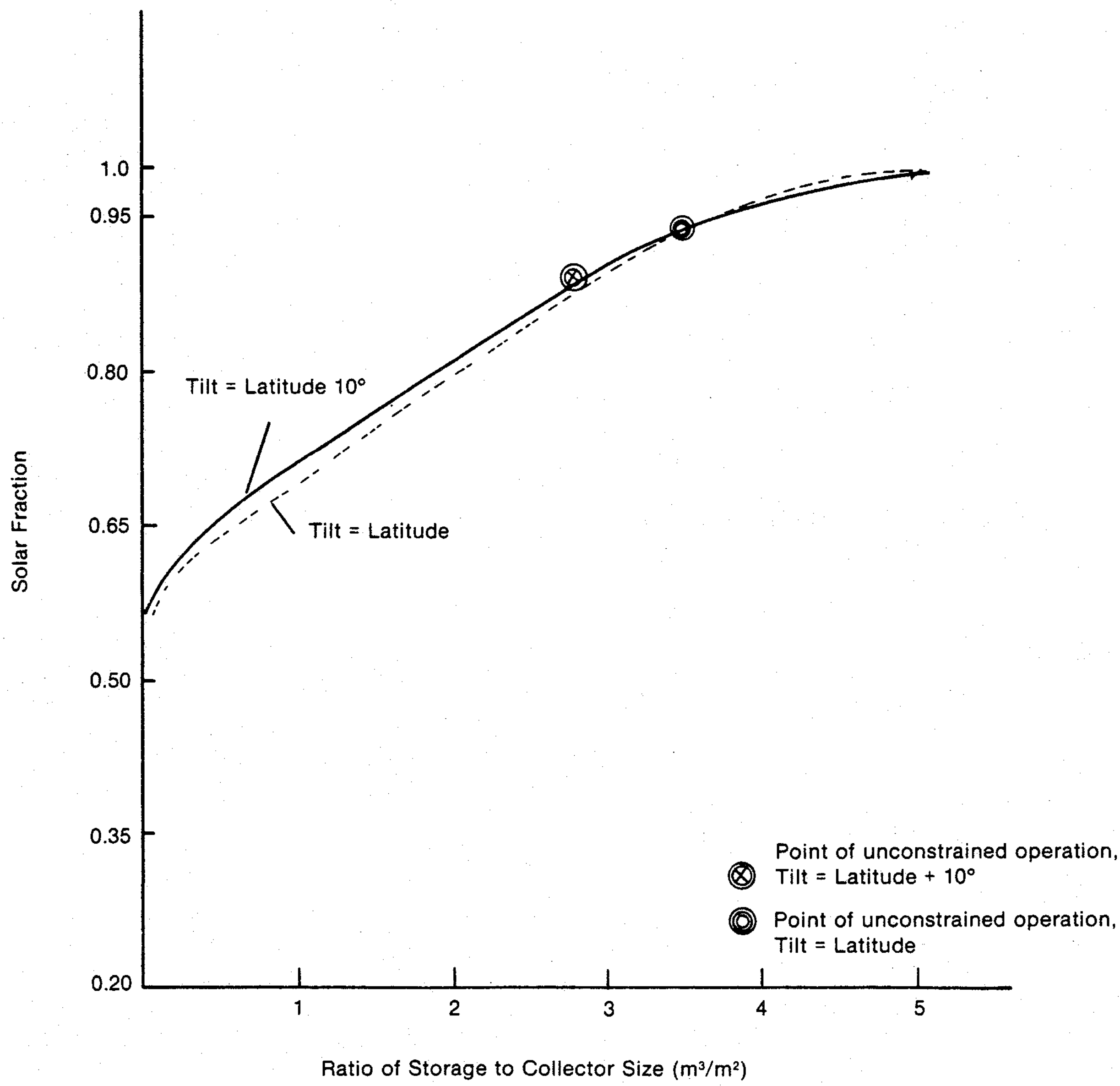


Figure 3-12. System Performance with Varying Collector Tilt
System is for Boston, Mass., SUB-50 standard load, space heat system with flat-plate collectors. Collector size is 2800 m².

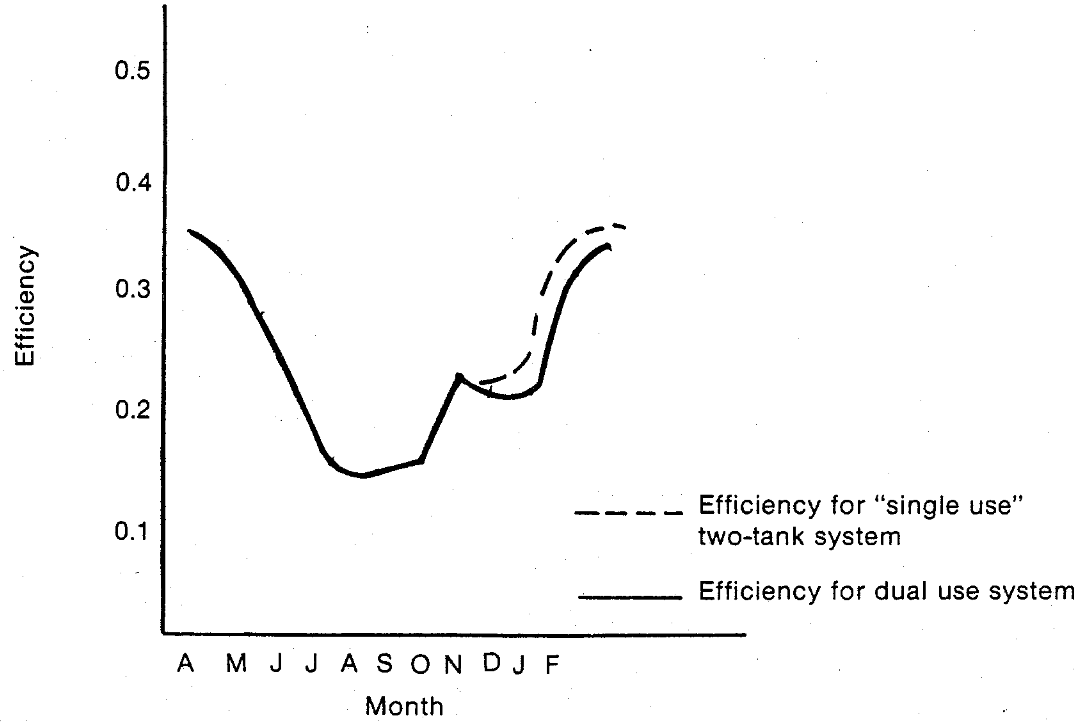
3.8 TWO-TANK SYSTEMS

A two-tank system improves system efficiency by permitting collection of low-temperature solar heat on a daily basis while the storage tank is fully charged. Figures 1-3 and 1-4 illustrate the operation and efficiency of the two-tank system, which, in effect, functions as a diurnal system during November through January with annually stored heat providing backup.

In the original concept as presented by Cha, Conner, and Mueller (1979), the daily storage tank in the two-tank system was used only to collect low-temperature solar heat during the late fall and early winter. When used in a combined space heat and hot water system, the daily storage tank may perform the additional function of collecting high-temperature heat for hot water when the annual storage tank is fully discharged. Figure 3-13 illustrates this type of operation. During the late winter months, the temperature of the annual storage tank drops to 30°-35°C. Because of its size, the annual storage tank does not heat up more than a few degrees on sunny days. As a result, only hot water preheat can be supplied during the late winter. During this period, the diurnal tank could be heated to 60°C on sunny days and used to provide hot water while the annual storage tank continued to provide space heat.

The algorithm used for this type of operation is as follows. As long as the annual tank temperature remains above 55°C, the diurnal tank is used to collect low-temperature heat. Heat for the load is taken first from the diurnal tank if available, driving down the temperature. Solar heat is collected for whichever storage tank is at the lowest temperature, thus providing the most efficient collection of solar heat. When the annual storage-tank temperature drops below 55°C, the mode of operation changes. Solar collection is used to heat the diurnal tank until its temperature reaches 60°C. When the diurnal tank temperature exceeds 60°C, solar collection is used to heat the annual storage tank. The diurnal tank is used preferentially to provide hot water. In this way, the two-tank system improves collection efficiency during November and December and also provides solar hot water in March and April.

Simulation results show that using the two-tank system in this way can result in a 3%-5% improvement in performance in comparison with a two-tank system using the daily storage tank only to collect low-temperature heat. This improvement occurs only in systems with a large solar fraction (85% or over). The major effect of this "dual use" of the two-tank system is to increase the amount of solar hot water provided. A single-tank system typically provides 80% of the hot water load, even when the system is sized to provide 100% of the space heat load. A two-tank system used only to collect low temperature heat (single use) would provide 85% of the hot water load along with 100% space heating, while with dual use the percentage of the hot water load supplied jumps to 90% or more. Interestingly, dual use also results in slight improvements in the percentage of the space heat load provided by the system. These improvements occur on the coldest days, when the heat exchange capacity within the building is too small to meet the building load with low-temperature heat from the annual storage tank. On these days, the diurnal storage tank provides heat at a temperature high enough to meet the building load. When the solar fraction is less, dual use of the two-tank system neither provides a significant improvement in performance nor lowers system performance when compared to single use of the two-tank system.



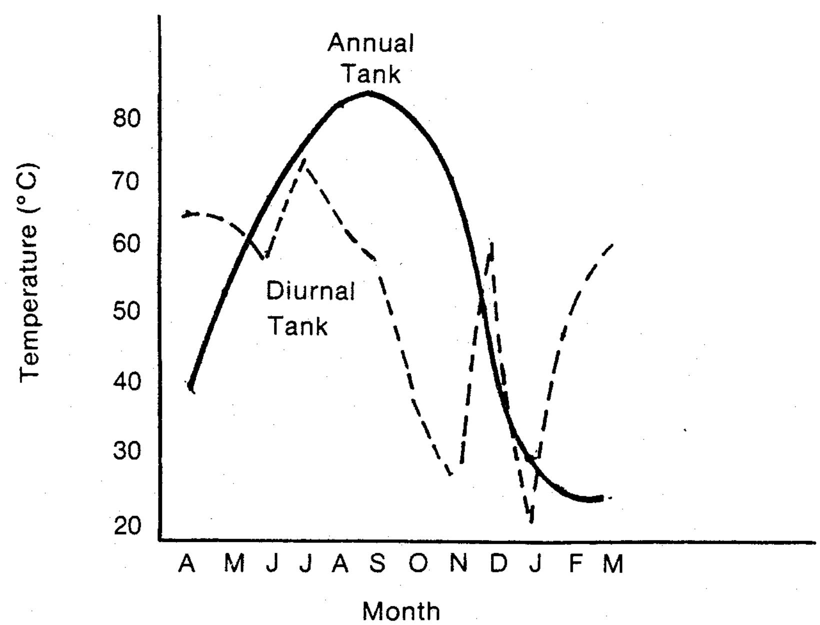


Figure 3-13. Efficiency and End-of-Month Storage Temperature for a "Dual Use" Two-Tank System

System is for flat-plate collector system; Boston, Mass., TUB-50, standard load.

A comparison of the performance and trade-off graphs in Appendix C indicates that two-tank systems show more nearly linear characteristics than do single-tank systems in the intermediate storage region (Region B). This is probably caused by the variation in collector efficiency with increasing storage size. As explained previously in Sec. 1.0, single-tank systems show a drop in collector efficiency as the transition from diurnal to annual storage is made. No such drop in efficiency occurs with a two-tank system.

SECTION 4.0

SYSTEM ECONOMICS

Results from the previous section indicate that near-100% annual storage systems may be economically preferable to the more common 50% solar heating systems with diurnal storage. In this section, system economics will be examined in greater detail. The analysis will be based on three tests for cost-effectiveness: the collector/storage trade-off, the value added by storage, and the overall system evaluation. The trade-off and value-added tests are used to compare annual storage systems with solar heating systems lacking annual storage, while the overall evaluation compares solar and conventional heating systems. Only when all three indicators favor annual storage is such a system cost-effective.

System economics are difficult to assess because system costs vary greatly. This analysis will assume that system cost in 1979 dollars is the sum of the following three components (Baylin et al. 1980b, Drew and Selvage 1980, King and Carlock 1979):

- Collector cost at $140/m^2 for flat-plate collectors or $200/m^2 for evacuated-tube collectors,
- Auxiliary costs (piping, ductwork, etc) at $100/m^2 collector area, and
- Storage cost as found from the equation (Drew and Selvage 1980)

$$\text{Cost} = 7.2\ V_s + 530\ V_s^{2/3} \text{ for volume } V_s \text{ in m}^3.$$

This equation yields a cost of $30-$50/m^3 for the system sizes included here.

Each of these costs is subject to great variation. Estimates for collector and storage costs may range from one-half to twice the given values. Collector and auxiliary costs assumed here represent a minimum cost estimate based on a survey of solar heating installations (King and Carlock 1979). Storage costs may be much higher if poor soil conditions exist or much lower with innovative technologies (e.g., aquifers, solar storage ponds, ferrocement tanks). The assumed storage costs are based on surveys of the costs of concrete and steel storage tanks (Baylin et al. 1980b, Drew and Selvage, 1980).

The collector/storage trade-off, as explained in Sec. 3.1, determines whether annual storage is preferable to a system with increased collector size substituted for storage. Based on the above costs, the breakeven point for annual storage will be a trade-off of 0.1-0.3 m^2/m^3. Annual storage systems are therefore strongly favored in the three northern cities, where the trade-offs are 0.4 m^2/m^3 or larger. In Albuquerque, the trade-off rate is 0.15-0.25 m^2/m^3, indicating that a diurnal or weekly storage system with a larger collector area may sometimes be favored over an annual storage system.

The value added by storage is simply the dollar value of the additional energy supplied each year (for a fixed collector area) by adding annual storage to a solar heating system. If the value of the added energy is less than the incremental cost of the larger storage system, then annual storage is not economically justified. A diurnal solar heating system with a backup heating source substituted for annual storage would be preferred.

For the annual storage systems considered, the yearly energy value added by storage ranges from 130 to 210 MJ/m^3. The net added cost is $20-$30/m^3 for large apartments and $35-$60/m^3 for districts of single family houses, and includes the cost of the district heating system (Baylin et al., 1980b).

The annual cost of a capitalized investment such as the storage system can be viewed as the annual payment that would amortize a loan over the life of the system. This "levelized annual cost" can then readily be converted to the life-cycle cost of the energy provided by the storage system by dividing the levelized annual cost by the energy supplied by the system. Because different purchasers will apply different discount rates for evaluating the cost-effectiveness of systems, costs will be illustrated for several different discount rates. Assuming that a system costs $30/m^3 and provides 180 MJ/m^3 with a useful life of 30 years, the cost of the energy supplied is

- 6.4¢/kWh for a 10% discount rate,
- 5.3¢/kWh for an 8% discount rate, and
- 3.5¢/kWh for a 4% discount rate.

These costs may alternatively be viewed as break-even costs for the storage system with a 10% discount rate and 0%, 2%, and 6% real escalation in the annual cost of conventional fuels; i.e., if a life-cycle cost analysis is performed for a 10% discount rate and the real cost of electricity is assumed to increase by 2% annually, the annual storage system considered would be preferable wherever the cost of backup heat now exceeds 5.3¢/kWh.

Overall system economics are evaluated similarly by calculating life-cycle/break-even energy costs. Table 4-1 presents costs for combined space heating and hot water systems based on the above solar system cost estimates and performance results for the systems and locations considered in this study. Results indicate that annual storage systems may be cost-effective in large parts of the United States if high fuel escalation rates are assumed. Incorporating the solar tax credits would lead to similar conclusions for lower fuel escalation rates.

Due to economies of scale in storage, annual storage systems are most advantageous for large apartment complexes or districts. Note that the cost of energy from the storage component is often equal to or slightly less than the cost of energy from the entire system. Consequently, the cost of energy from the system will remain essentially constant as the solar fraction is increased to 100%, as shown in Fig. 3-9. Whenever the storage energy cost is less than or equal to the system energy cost, near-100% annual storage systems will be preferable to smaller diurnal systems.

Table 4-1. LIFE-CYCLE/BREAK-EVEN ENERGY COST OF ANNUAL STORAGE SYSTEMS

(Life-cycle/break-even costs in 1979 ¢/kWh are calculated for flat-plate, two-tank systems for a 50 single-family house district that provides heat and hot water. Break-even costs assumed are a 10% discount rate, 30-year amortization period, and either 2% or 6% fuel escalation per year. This corresponds to life-cycle energy costs with 8% and 4% discount rates respectively. Solar energy system costs are found from the equation:

$$\text{Cost} = 240\ A_c + (7.2\ V_s + 530\ V_s^{2/3}),$$

for a collector size A_c in m^2 and storage size V_s in m^3.)

Construction	Fuel Escalation Rate	Break-even Cost in 1979 ¢/kWh			
		Boston	Medford	Bismarck	Albuquerque
Standard	2%	7.5	5.7	6.8	4.1
	6%	4.8	3.7	4.4	2.7
Passive	2%	9.1	7.6	9.1	4.9
	6%	5.8	4.9	5.8	3.1
Superinsulated	2%	9.8	8.1	10.2	4.9
	6%	6.3	5.2	6.6	3.1

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SECTION 5.0

DESIGN METHODS

Design tools for annual storage systems were the subject of a recent study by the authors (Baylin and Sillman 1980). A model of annual storage systems using a utilization formula for collector efficiency and bimonthly steps was found to yield accurate results for standard building loads and was recommended for system design. The question is whether a bimonthly simulation remains accurate when used with passive, superinsulated, or other conserving building loads. An examination of this question is presented below.

For single-tank annual storage systems, the nature of the building load has no effect on design tool accuracy. The bimonthly utilization model is found to perform accurately with all bulding load types, so long as the accurate monthly building load data are provided. A possible problem arises only when the storage tank size is small, so that month-to-month variation in storage tank temperature may exceed 20°C. This will not happen for annual storage systems at the point of unconstrained operation, even if the hot water load is large. For two-tank systems, however, some inaccuracy may result from using a bimonthly model for system design with an energy-conserving building.

A simple method for sizing systems near the point of unconstrained operation has been developed by Drew and Selvage (1980). A summary of their method is presented below:

(1) The desired maximum and minimum storage temperature is selected for the yearly cycle.

(2) Storage temperature for each month is calculated assuming that storage temperature follows a sinusoidal pattern over the year with maximum occurring on 1 October and minimum on 1 April (the exact time of yearly minimum and maximum can be adjusted).

(3) Collector efficiency for each month is calculated by the utilization method (Klein 1978), based on the above monthly storage temperatures. Solar heat collection for each month is also calculated.

(4) The amount of heat supplied to the load from storage is calculated for each month based also on the assumed monthly storage temperature.

(5) Collector and storage sizes for the above system are found by solving two simultaneous equations, one for system performance from 1 April to 30 September and one for performance from 1 October to 31 March. During the summer half, collected solar energy must equal the sum of (1) load for the period, (2) storage losses, and (3) the amount of energy needed to raise storage from its minimum yearly temperature to its maximum. During the winter, the heat supply is equal to collected solar energy plus the amount of heat liberated when storage temperature drops from its maximum to its minimum value. This heat supply must be equal to solar load plus storage losses. This analysis results in two equations with only collector and storage sizes unknown. Collector and storage size for the system may thus be found.

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SECTION 6.0

CONCLUSIONS

The study presented should provide a comprehensive look at the design trade-off and performance of annual-cycle solar heating systems. The following are general conclusions.

- The performance curves for active solar heating systems with storage show three distinct regions: a region of diurnal storage, an intermediate region, and a region of annual storage. System performance is found to increase linearly as storage size increases throughout the intermediate region. The likely economic optimum occurs at the point of "unconstrained operation," at which the storage tank is large enough to store all heat collected in summer.
- In contrast to diurnal storage systems, annual storage systems show only slightly diminishing returns as the solar heat fraction increases. Optimal annual storage systems are sized to meet nearly 100% of the building space heat loads. These near-100% systems may be preferable to the more common 50%-solar systems in many cases.
- Also in contrast to diurnal systems, annual storage systems perform efficiently when combined with passive solar or other energy-efficient building designs.
- The size of storage necessary for an annual storage system at the point of unconstrained operation varies greatly. Space-heating systems typically have a storage-to-collector ratio of 3-5 m^3:1 m^2. Combined space- and water-heating systems have proportionately less storage, especially when the space-heating load is small. In some cases, a system may have a storage-to-collector ratio of 1 m^3:1 m^2 or less and still function as an unconstrained annual storage system.
- Inclusion of annual storage in an active solar heating system results in a net added energy of 130-210 MJ/m^3 per year. Based on a net added energy of 180 MJ/m^2 each year and a cost of $30/$m^3$, the break-even cost of energy added by annual storage is 4¢-6¢/kWh. The total system breaks even against an energy source that costs 4¢-9¢/kWh.

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SECTION 7.0

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APPENDIX A

BASIC ASSUMPTIONS IN THE SOLAR HEATING SYSTEM

A. COLLECTOR PERFORMANCE

	$F_r\,(\alpha\tau)$	F_rU_l [W/m^2]
Flat-plate collector	0.661	6.104
Evacuated-tube collector	0.397	1.170

*The terms $F_r\,(\alpha\tau)$ and F_rU_l are terms from the instantaneous solar collection equation:

$$Q_c = F_r\,(\alpha\tau)\,I - F_rU_l\Delta T$$

where Q_c is collected solar heat, I is incident solar radiation, and ΔT is the difference between the collector, and ambient temperatures. Collector temperature is assumed equal to the average storage temperature.

B. STORAGE

Storage losses are calculated based on a constant storage U-value of 0.11 W/m^2°C. Storage losses are calculated relative to ground temperature, which is assumed equal to average year-round ambient temperature.

Maximum Storage Temperature: 79.5° C.

C. TRANSMISSION LOSSES

Transmission losses from collector to storage and from storage to load are ignored. They are assumed to be accounted for by storage losses.

D. HEAT EXCHANGE CAPACITY

Ability of the heating system to meet the load depends on (a) size of the load, (b) size of heat exchange between heat source and load, and (c) temperature difference between heat source and room temperature. Assuming that building load is proportional to the difference between ambient and room temperature, the fraction of the building load that may be supplied by a solar heating system is:

$$\text{Solar fraction} = X_h \, \frac{T_s - T_r}{T_r - T_a}$$

where T_r is room temperature (assumed to be 20° C in this study), T_s is the temperature of the heat source, T_a is ambient temperature, and X_h is a dimensionless coefficient (Klein et al. 1977). In this study the coefficient X_h has the following values:

For single-tank systems, $X_h = 2$,

For two-tank systems, $X_h = 1$ for the diurnal tank, and

$X_h = 1$ for the annual tank.

E. HOT WATER PREHEAT

The fraction of the hot water load that may be met by the solar heating system is similarly dependent on a heat-exchange effectiveness formula. In this simulation the formula is

$$\text{Hot water fraction} = \frac{T_s - 10}{52 - 10}$$

where T_s is heat-source temperature. This assumes a cold-water temperature of 10°C, a hot-water temperature of 49°C, and a heat-exchange effectiveness of 92%.

APPENDIX B

CALCULATION OF PASSIVE AND CONSERVING BUILDING LOADS

Passive and conserving loads were included in this study in order to investigate what effects the load may have on the performance of active solar heating systems. Consequently, the passive-load algorithm need not find the precise load of a particular building. The purpose of the load algorithm is to generate a load pattern that reflects the daily and monthly load variation of a passive or superinsulated building design, rather than an exact load.

The load algorithm requires four input parameters:

- Building gross shell loss coefficient, in watts per degree Centigrade;
- Effective passive collection area, in square meters (the effective area is assumed modified to reflect window angles, transmission losses, and other losses);
- Miscellaneous heat gain, in watts, due to inhabitants and electric appliances; and
- Effective thermal-mass capacity in watt-hours. This term gives the quantity of heat which may be stored without bringing discomfort to the residents.

The algorithm calculates the heat load for each day in two periods, one for daytime and one for nighttime. For each period the following five steps are performed.

(1) Building gross shell loss for the period is calculated based on the difference between room temperature (assumed to be a constant 20°C) and ambient temperature and the shell-loss coefficient. This step parallels the degree-day method of calculating building loads.

(2) Miscellaneous heat gain for the period is calculated and the gain is subtracted from the gross shell load. If the miscellaneous heat gain exceeds the load, excess heat is stored in thermal mass.

(3) Passive gain in daytime is calculated from the total daily radiation and the effective passive collection area. The passive gain is subtracted from the building load remaining at the end of Step 2. Again, if excess heat remains, it is added to passive storage.

(4) If necessary, heat is removed from thermal mass to meet whatever positive net building load remains at the end of Step 3. If stored heat is insufficient to meet the building load at this step, the remainder becomes the net building load for the period and will be met by either active solar or auxiliary heat.

(5) The amount of heat stored in thermal mass is carried over to the next period. The amount of passively stored heat is not allowed to exceed the effective thermal mass capacity.

When the parameters are set properly, this algorithm generates a load pattern that meets the criteria for use in this study. The load size may be set appropriately; and the load changes from day to day, reflecting the amount of insolation. For passive construction, the effective passive collection area is sized to meet nearly all the load on a sunny winter day. Thermal-mass capacity is set to accommodate nearly all the load of a mild winter night. Thus, on a sunny, mild winter day there would be virtually no load, while on a sunny-and-cold or cloudy-and-mild winter day there would be a moderate load. Parameters for a superinsulated house are set in the same way, although both passive collection area and thermal-mass capacity are much reduced because the gross shell loss is reduced. These sizings result in a building that obtains 50% of its spaceheating requirements from passive gain in a northern location. As described in Sec. 2.6, parameters for large apartment buildings were set differently to reflect limitations on the use of passive solar construction with such apartment buildings.

Table B-1 shows a comparison between results of the passive load algorithm and data generated by the SUNCAT 2.4 hourly passive simulation (Palmiter). As shown in Table B-1, the passive algorithm cannot be used accurately to predict actual building loads. The monthly and daily loads, however, are all reasonably close to the SUNCAT data. Simulation results with the passive load algorithm should therefore reflect accurately the performance of active solar heating when coupled with a passive building load pattern. The monthly and daily load patterns for superinsulated buildings are designed to approximate the load pattern of the Saskatchewan Conservation House (Besant 1978) and the Lyngby House (Esbensen and Korsgaard 1977).

Tables B-2 and B-3 give the values of the parameters and building performance for each of the types of buildings and each location used in this study. SUB 50, TUB 50, and HUB 200 refer to the building types, explained in Sec. 2.0.

Table B-1. COMPARISON BETWEEN PASSIVE LOAD ALGORITHM AND SUNCAT SIMULATION

Data below compare monthly and daily loads in GJ generated by the passive load algorithm with loads generated by the SUNCAT hourly simulation. Simulation is for Madison, Wis., using TMY meteorological data. The passive load algorithm used the following parameters:

Gross shell loss coeff. 48 MJ/h°C
Miscellaneous heat gain 80 MJ/h
Passive gain effective area 700 m^2
Effective thermal mass capacity 10 GJ.

Monthly Loads			Daily Loads		
Month	Passive Algorithm	SUNCAT	Day	Passive Algorithm	SUNCAT
Apr.	1.4	1.8	Jan. 1	0.38	0.40
May	0.6	0.7	Jan. 2	0.22	0.21
June	0	0	Jan. 3	0.24	0.15
July	0	0	Jan. 4	0.37	0.30
Aug.	0	0	Jan. 5	0.28	0.23
Sept.	0	0	Jan. 6	0.34	0.30
Oct.	1.0	1.5	Jan. 7	0.26	0.25
Nov.	6.6	6.0	Jan. 8	0.42	0.48
Dec.	11.4	10.8	Jan. 9	0.54	0.42
Jan.	13.6	12.2	Jan. 10	0.48	0.36
Feb.	9.4	9.4			
Mar.	6.5	6.0			

Table B-2. BUILDING PARAMETERS

LOAD TYPE	GROSS SHELL LOSS COEFFICIENT, 10^6 J/h °C.	MISC. HEAT GAIN 10^6 J/h	PASSIVE GAIN EFFECTIVE AREA (m^2)	EFFECTIVE THERMAL MASS CAPACITY 10^9 J
	BOSTON, MASS.			
SUB 50				
Standard	53	80	0	0
Passive	40	80	700	10
Superinsulated	15	70	250	4
TUB 50				
Standard	22	40	0	0
Passive	16	40	220	4
Superinsulated	7	32	100	2
HUB 200				
Standard	56	120	0	0
Conserving	25	100	250	5
	BISMARCK, N. DAK.			
SUB 50				
Standard	52	80	0	0
Passive	40	80	800	12
Superinsulated	13	70	250	4
TUB 50				
Standard	22	40	0	0
Passive	16	40	300	5
Superinsulated	6	32	120	2
HUB 200				
Standard	54	120	0	0
Conserving	22	100	300	5

Table B-2. BUILDING PARAMETERS (Concluded)

LOAD TYPE	GROSS SHELL LOSS COEFFICIENT 10^6 J/h °C	MISC. HEAT GAIN 10^6 J/h	PASSIVE GAIN EFFECTIVE AREA (m^2)	EFFECTIVE THERMAL MASS CAPACITY 10^9 J
	MEDFORD, OREG.			
SUB 50*				
Standard	53	80	0	0
Passive	40	80	700	10
Superinsulated	15	70	250	4
TUB 50*				
Standard	22	40	0	0
Passive	16	40	220	4
Superinsulated	7	32	100	1
HUB 200*				
Standard	56	120	0	0
Conserving	25	100	250	5
	ALBUQUERQUE, N. MEX.			
SUB 50				
Standard	53	80	0	0
Semipassive	35	70	300	5
Passive	40	80	600	10
TUB 50				
Standard	22	40	0	0
Passive	16	40	200	4
HUB 200				
Standard	56	120	0	0
Conserving	30	100	200	4

Table B-3. BUILDING LOADS

LOAD TYPE	GROSS SHELL LOSS (GSL) 10^{12} J/yr	% of GSL SUPPLIED BY MISC. HEAT	% of GSL SUPPLIED BY PASSIVE GAIN	NET SPACE HEAT LOAD 10^{12} J/yr	ANNUAL HOT WATER LOAD 10^{12} J
		BOSTON, MASS.			
SUB 50					
Standard	4.441	0.125	0.000	3.890	0.876
Passive	3.352	0.166	0.472	1.216	0.840
Superinsulated	1.257	0.356	0.388	0.322	0.548
TUB 50					
Standard	1.844	0.149	0.000	1.570	0.876
Passive	1.307	0.209	0.397	0.516	0.840
Superinsulated	0.587	0.350	0.354	0.175	0.511
HUB 200					
Standard	4.693	0.173	0.000	3.880	1.752
Conserving	2.095	0.312	0.280	0.855	1.460
		BISMARCK, N. DAK.			
SUB 50					
Standard	6.602	0.091	0.000	6.000	0.975
Passive	5.079	0.119	0.478	2.047	0.975
Superinsulated	1.651	0.297	0.396	0.506	0.657
TUB 50					
Standard	2.793	0.107	0.000	2.495	0.975
Passive	1.981	0.151	0.457	0.776	0.975
Superinsulated	0.762	0.295	0.410	0.225	0.657
HUB 200					
Standard	6.856	0.129	0.000	5.975	1.945
Conserving	2.793	0.256	0.320	1.186	1.643

Table B-3. **BUILDING LOADS** (Concluded)

LOAD TYPE	GROSS SHELL LOSS (GSL) 10^{12} J/yr	% of GSL SUPPLIED BY MISC. HEAT	% of GSL SUPPLIED BY PASSIVE GAIN	NET SPACE HEAT LOAD 10^{12} J/yr	ANNUAL HOT WATER LOAD 10^{12} J
MEDFORD, OREG.					
SUB 50					
Standard	4.101	0.154	0.000	3.471	0.803
Passive	3.095	0.207	0.497	0.918	0.803
Superinsulated	1.161	0.433	0.369	0.231	0.511
TUB 50					
Standard	1.702	0.183	0.000	1.391	0.803
Passive	1.207	0.261	0.423	0.384	0.803
Superinsulated	0.542	0.426	0.347	0.124	0.511
HUB 200					
Standard	4.333	0.212	0.000	3.415	1.606
Conserving	1.934	0.382	0.299	0.620	1.460
ALBUQUERQUE, N. MEX.					
SUB 50					
Standard	3.559	1.145	0.000	3.044	0.840
Semipassive	2.351	0.191	0.502	0.724	0.730
Passive	2.686	0.191	0.703	0.291	0.840
TUB 50					
Standard	1.477	0.171	0.000	1.224	0.840
Passive	0.237	0.636	0.136	0.840	0.840
HUB 200					
Standard	3.761	0.198	0.000	3.016	1.679
Conserving	2.015	0.299	0.386	0.636	1.314

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APPENDIX C

SIMULATION RESULTS

The following tables offer a summary of the numerical results of this study. Included are representative system sizes for each type of system investigated, and system descriptions in terms of the parameters discussed in Sec. 3.0.

The tables present collector and storage sizes for annual storage systems designed to meet 95% of the system space heat load. Both the fraction of hot water provided and the total solar fraction vary among the systems presented. This criterion was selected for system sizing in order to avoid misleading results that can occur when a predominantly hot water system is compared with a predominantly space heating system with the same solar fraction. As discussed in Secs. 3.2 and 3.5, optimal annual storage systems typically provide 95%-100% of the building space heat load but only 80%-90% of the hot water load. Proper system sizing is therefore based on the system's projected ability to meet the space-heating load rather than the total load. All system sizes presented are for points of unconstrained annual storage operation, as defined in Sec. 3.0.

In the two-tank systems, the second storage tank is always sized according to the collector area (A_c), using the formula

$$V_s\,(m^3) = 0.075\,A_c\,(m^2)\ .$$

In addition to collector size, storage size, and total solar fraction, the tables give the following parameters:

- Overall system efficiency for the annual storage system. This is defined as the total heat delivered to the load, divided by the total energy incident on the collector for the year.
- Diurnal solar fraction. This is the solar fraction for a diurnal system with the same collector area as the given annual system. Storage size in cubic meters is one-fifth the collector size in square meters for the diurnal system. If the annual storage system is a two-tank system, the diurnal solar fraction is also based on a two-tank system, with the same-sized second tank as in the annual system.
- Net added energy. This is based on a comparison of the performance of the annual storage system and the diurnal system described above. Net energy is calculated by the following formula:

$$\text{Net energy} = \frac{\text{heat delivered by annual system} - \text{heat delivered by diurnal system}}{\text{annual storage volume} - \text{diurnal storage volume}}\ .$$

The annual and diurnal systems, as sized here, represent the boundaries of the intermediate storage region in the system-performance graphs (Region B) as described in Sec. 3.0. As explained in the text, the net energy added by storage gives the slope of the system-performance curve, which is usually a linear curve in this region.

- Collector storage trade-off rate. This parameter gives the rate at which collector area may be replaced by storage volume in systems with the same total solar fraction as the annual storage system. As with the value of storage, the trade-off is close to linear. Systems are for both space heat and hot water, with tilt equal to latitude plus 10 degrees, unless mentioned otherwise.

Also presented are the system-performance and collector/storage trade-off graphs for the locations, collector types, and building designs included in this study. System plots are all for SUB-50 systems. Both space heat and combined systems are presented.

The system performance curves represent a number of different collector sizes. Collector sizes for each plot are listed below the graph. The y-axis gives solar fraction ranging from 0.2 to 1.0. The x-axis gives the ratio of storage size to collector size, ranging from zero to 5 m^3/m^2 collector area.

The trade-off graphs present isoquant curves for solar fractions of 0.75, 0.80, 0.85, 0.90, 0.95, and 0.99. For combined systems, the last isoquants (with solar fractions of 0.95 and 0.99) may be omitted. This omission occurs because a combined system may need to supply not just 100% solar space heat but also an inordinately large percentage of the hot water load in order to meet a high combined solar fraction. Such systems would have to be oversized. A typical combined load system may meet 100% of the space heat load and 85% of the hot water load, for a combined solar fraction of 92%. In such a case, isoquants for higher solar fractions would be omitted.

In the trade-off graphs, storage volume is plotted on the y-axis and collector area on the x-axis. The scale of the x- and y-axes are in the same proportion to each other for all trade-off graphs, with one square meter collector area corresponding in scale to one cubic meter storage. Also plotted on the trade-off graphs are discrete points representing the region of unconstrained operation.

SIMULATION RESULTS
BOSTON, MASS.
Flat-Plate Collector - Single-Tank System

LOAD TYPE	COLLECTOR AREA (m^2)	STORAGE VOLUME (m^3)	EFFICIENCY	SOLAR FRACTION	DIURNAL SOLAR FRACTION	NET ADDED ENERGY MJ/m^3	TRADE-OFF m^2 collector/m^3 storage
SUB 50							
Standard	3830	8880	0.230	0.925	0.717	124	0.47
Passive	1800	3960	0.207	0.905	0.677	129	0.63
Superinsulated	850	1180	0.183	0.889	0.788	87	0.47
SUB 50 - space heat only							
Standard	3120	8740	0.237	0.950	0.660	140	0.55
Passive	1100	3800	0.210	0.950	0.482	160	0.83
Superinsulated	350	1000	0.174	0.950	0.486	160	1.10
SUB 1							
Standard	97	172	0.182	0.929	0.792	90	0.47
Passive	54	68	0.138	0.905	0.795	80	0.50
Superinsulated	24	20	0.131	0.901	0.857	51	0.40
TUB 50							
Standard	2000	3600	0.220	0.903	0.768	110	0.43
Passive	1250	1700	0.192	0.885	0.794	85	0.40
Superinsulated	700	560	0.174	0.890	0.852	64	0.35
HUB 200							
Standard	4500	9100	0.227	0.909	0.744	115	0.45
Conserving	2100	2550	0.200	0.885	0.800	100	0.42

*System with collector tilt equal to latitude.

SIMULATION RESULTS
BOSTON, MASS.
Evacuated-Tube Collector - Single-Tank System

LOAD TYPE	COLLECTOR AREA (m^2)	STORAGE VOLUME (m^3)	EFFICIENCY	SOLAR FRACTION	DIURNAL SOLAR FRACTION	NET ADDED ENERGY MJ/m^3	TRADE-OFF m^2 collector/m^3 storage
SUB 50							
Standard	3000*	9200	0.284	0.921	0.610	172	0.47
Passive	1350	3750	0.271	0.897	0.608	172	0.55
Superinsulated	590	1180	0.258	0.877	0.713	135	0.42
SUB 50 - space heat only							
Standard	2600*	8400	0.278	0.950	0.578	180	0.45
Passive	850	3200	0.272	0.950	0.406	210	0.77
Superinsulated	260	1000	0.236	0.950	0.404	170	0.77
SUB 1							
Standard	73*	200	0.226	0.932	0.675	125	0.38
Passive	36	80	0.204	0.892	0.694	115	0.33
Superinsulated	16	25	0.191	0.878	0.791	90	0.25
TUB 50							
Standard	1500*	4000	0.282	0.895	0.665	160	0.60
Passive	900	2050	0.256	0.875	0.717	120	0.33
Superinsulated	460	750	0.259	0.858	0.771	90	0.25
HUB 200							
Standard	3500*	9300	0.284	0.904	0.650	165	0.40
Conserving	1460	3000	0.269	0.872	0.708	140	0.40

*System with collector tilt equal to latitude.

SIMULATION RESULTS
BOSTON, MASS.
Flat-Plate Collector - Two-Tank System

LOAD TYPE	COLLECTOR AREA (m^2)	STORAGE VOLUME (m^3)	EFFICIENCY	SOLAR FRACTION	DIURNAL SOLAR FRACTION	NET ADDED ENERGY MJ/m^3	TRADE-OFF m^2 collector/m^3 storage
SUB 50							
Standard	3550	7840	0.254	0.944	0.691	170	0.55
Passive	1800	3700	0.215	0.944	0.691	155	0.67
Superinsulated	850	1180	0.195	0.946	0.802	145	0.83
SUB 50 - space heat only							
Standard	2800	8000	0.263	0.950	0.620	175	0.53
Passive	1100	3600	0.212	0.950	0.500	170	0.63
Superinsulated	350	1000	0.179	0.950	0.520	155	0.77
SUB 1							
Standard	90	155	0.202	0.944	0.764	130	0.55
Passive	50	65	0.156	0.946	0.791	100	0.60
Superinsulated	23	25	0.141	0.944	0.877	52	0.35
TUB 50							
Standard	1900	3300	0.238	0.938	0.751	155	0.53
Passive	1200	1700	0.215	0.941	0.791	145	0.60
Superinsulated	680	600	0.191	0.944	0.863	120	0.60
HUB 200							
Standard	4250	8600	0.248	0.939	0.725	165	0.50
Conserving	2000	2700	0.216	0.935	0.790	145	0.55

*System with collector tilt equal to latitude.

SIMULATION RESULTS
BOSTON, MASS.
Evacuated-Tube Collector - Two-Tank System

LOAD TYPE	COLLECTOR AREA (m^2)	STORAGE VOLUME (m^3)	EFFICIENCY	SOLAR FRACTION	DIURNAL SOLAR FRACTION	NET ADDED ENERGY MJ/m^3	TRADE-OFF m^2 collector/m^3 storage
SUB 50							
Standard	2800*	8100	0.310	0.941	0.612	210	0.47
Passive	1360	3800	0.283	0.942	0.631	185	0.45
Superinsulated	590	1180	0.271	0.936	0.734	165	0.47
SUB 50 - space heat only							
Standard	2250*	8200	0.325	0.950	0.542	200	0.45
Passive	820	3700	0.282	0.950	0.420	185	0.40
Superinsulated	250	1000	0.246	0.950	0.426	180	0.63
SUB 1							
Standard	70	160	0.256	0.944	0.685	170	0.45
Passive	35	77	0.222	0.945	0.708	140	0.45
Superinsulated	16	23	0.204	0.941	0.818	110	0.50
TUB 50							
Standard	1460	3400	0.307	0.935	0.670	210	0.45
Passive	900	1700	0.282	0.938	0.735	180	0.45
Superinsulated	460	720	0.280	0.930	0.788	160	0.39
HUB 200							
Standard	3350	8200	0.316	0.938	0.651	220	0.50
Conserving	1450	2900	0.292	0.931	0.723	195	0.47

*System with collector tilt equal to latitude.

SIMULATION RESULTS
MEDFORD, OREG.
Flat-Plate Collector - Single-Tank System

LOAD TYPE	COLLECTOR AREA (m^2)	STORAGE VOLUME (m^3)	EFFICIENCY	SOLAR FRACTION	DIURNAL SOLAR FRACTION	NET ADDED ENERGY MJ/m^3	TRADE-OFF m^2 collector/m^3 storage
SUB 50							
Standard	2300	8400	0.283	0.920	0.618	160	0.67
Passive	1000*	4100	0.251	0.885	0.524	155	0.70
Superinsulated	500	1230	0.220	0.864	0.669	135	0.83
SUB 50 - space heat only							
Standard	1800	8300	0.301	0.950	0.563	180	0.70
Passive	600	3400	0.242	0.950	0.261	190	1.40
Superinsulated	170*	920	0.223	0.950	0.238	185	2.00
SUB 1							
Standard	60*	190	0.215	0.923	0.677	120	0.60
Passive	31	90	0.178	0.894	0.609	115	0.77
Superinsulated	14*	33	0.150	0.865	0.715	75	0.60
TUB 50							
Standard	1200*	3800	0.268	0.897	0.661	140	0.55
Passive	750	1600	0.232	0.861	0.671	155	1.10
Superinsulated	420	800	0.224	0.869	0.738	115	0.70
HUB 200							
Standard	2500*	9700	0.295	0.898	0.623	150	0.63
Conserving	1250	3200	0.244	0.857	0.684	120	0.55

*System with collector tilt equal to latitude.

SIMULATION RESULTS
MEDFORD, OREG.
Evacuated-Tube Collector - Single-Tank System

LOAD TYPE	COLLECTOR AREA (m^2)	STORAGE VOLUME (m^3)	EFFICIENCY	SOLAR FRACTION	DIURNAL SOLAR FRACTION	NET ADDED ENERGY MJ/m^3	TRADE-OFF m^2 collector/m^3 storage
SUB 50							
Standard	2200	8300	0.303	0.921	0.587	180	0.53
Passive	900*	3800	0.276	0.880	0.510	175	0.83
Superinsulated	400*	1180	0.259	0.852	0.640	145	0.67
SUB 50 - space heat only							
Standard	1800*	7700	0.305	0.950	0.540	195	0.63
Passive	580	3400	0.258	0.950	0.253	190	0.90
Superinsulated	160	900	0.235	0.950	0.237	190	1.00
SUB 1							
Standard	55	180	0.244	0.920	0.642	140	0.47
Passive	27	82	0.195	0.890	0.685	95	0.77
Superinsulated	12	27	0.188	0.858	0.696	100	0.55
TUB 50							
Standard	1100	3600	0.291	0.889	0.623	170	0.47
Passive	600*	1950	0.274	0.850	0.632	150	0.55
Superinsulated	340	800	0.261	0.855	0.708	130	0.55
HUB 200							
Standard	2400*	9000	0.305	0.896	0.594	180	0.50
Conserving	1100	3100	0.277	0.862	0.662	145	0.60

*System with collector tilt equal to latitude.

SIMULATION RESULTS
MEDFORD, OREG.
Flat-Plate Collector - Two-Tank System

LOAD TYPE	COLLECTOR AREA (m^2)	STORAGE VOLUME (m^3)	EFFICIENCY	SOLAR FRACTION	DIURNAL SOLAR FRACTION	NET ADDED ENERGY MJ/m^3	TRADE-OFF m^2 collector/m^3 storage
SUB 50							
Standard	2100*	7800	0.323	0.941	0.595	200	0.70
Passive	1050	3900	0.260	0.935	0.552	180	0.83
Superinsulated	500	1220	0.235	0.929	0.685	165	0.83
SUB 50 - space heat only							
Standard	1700	7200	0.333	0.950	0.544	210	0.67
Passive	550*	3500	0.246	0.950	0.280	180	0.83
Superinsulated	180	900	0.217	0.950	0.288	180	1.00
SUB 1							
Standard	55	165	0.250	0.939	0.653	160	0.55
Passive	32	86	0.176	0.932	0.630	130	0.55
Superinsulated	15	30	0.158	0.929	0.741	105	0.70
TUB 50							
Standard	1150	3350	0.300	0.929	0.654	195	0.60
Passive	770	1800	0.244	0.923	0.686	170	0.90
Superinsulated	420	820	0.244	0.925	0.750	150	0.90
HUB 200							
Standard	2600	7800	0.311	0.932	0.633	205	0.67
Conserving	1250	3000	0.261	0.919	0.694	170	0.83

*System with collector tilt equal to latitude.

SIMULATION RESULTS
MEDFORD, OREG.
Evacuated-Tube Collector - Two-Tank System

LOAD TYPE	COLLECTOR AREA (m^2)	STORAGE VOLUME (m^3)	EFFICIENCY	SOLAR FRACTION	DIURNAL SOLAR FRACTION	NET ADDED ENERGY MJ/m^3	TRADE-OFF m^2 collector/m^3 storage
SUB 50							
Standard	2000*	7600	0.331	0.934	0.601	200	0.77
Passive	900*	3850	0.294	0.930	0.528	190	0.77
Superinsulated	400*	1200	0.280	0.920	0.657	175	0.70
SUB 50 - space heat only							
Standard	1600*	7200	0.338	0.950	0.519	215	0.63
Passive	500*	3300	0.302	0.950	0.256	200	0.83
Superinsulated	160	880	0.235	0.950	0.267	190	1.10
SUB 1							
Standard	50	160	0.272	0.940	0.631	170	0.47
Passive	25	80	0.225	0.934	0.590	160	0.77
Superinsulated	12	27	0.200	0.924	0.720	125	0.60
TUB 50							
Standard	1020*	3500	0.330	0.921	0.618	190	0.53
Passive	600*	1950	0.297	0.914	0.649	120	0.45
Superinsulated	350	800	0.282	0.916	0.730	150	0.70
HUB 200							
Standard	2400*	8300	0.328	0.930	0.608	205	0.50
Conserving	1020*	3000	0.307	0.910	0.661	185	0.63

*System with collector tilt equal to latitude.

SIMULATION RESULTS
BISMARCK, N. DAK.
Flat-Plate Collector - Single-Tank System

LOAD TYPE	COLLECTOR AREA (m^2)	STORAGE VOLUME (m^3)	EFFICIENCY	SOLAR FRACTION	DIURNAL SOLAR FRACTION	NET ADDED ENERGY MJ/m^3	TRADE-OFF m^2 collector/m^3 storage
SUB 50							
Standard	5000	16500	0.218	0.935	0.684	113	0.70
Passive	2400	8200	0.193	0.922	0.623	118	0.83
Superinsulated	1000	2600	0.175	0.914	0.726	91	0.70
SUB 50 - space heat only							
Standard*	4000	17000	0.235	0.950	0.618	125	0.77
Passive	1000	7600	0.200	0.950	0.463	135	1.25
Superinsulated	470	2000	0.170	0.950	0.445	135	1.40
SUB 1							
Standard	130	360	0.168	0.935	0.749	80	0.63
Passive	70	210	0.136	0.923	0.705	66	0.50
Superinsulated	32	58	0.111	0.922	0.819	50	0.47
TUB 50							
Standard	2400	7800	0.217	0.922	0.710	100	0.67
Passive	1450	4000	0.184	0.913	0.734	85	0.53
Superinsulated	800	1440	0.167	0.913	0.822	65	0.45
HUB 200							
Standard	5500	17800	0.222	0.927	0.698	110	0.67
Conserving	2300	5700	0.186	0.914	0.750	90	0.60

*System with collector tilt equal to latitude.

SIMULATION RESULTS
BISMARCK, N. DAK.
Flat-Plate Collector - Two-Tank System

LOAD TYPE	COLLECTOR AREA (m^2)	STORAGE VOLUME (m^3)	EFFICIENCY	SOLAR FRACTION	DIURNAL SOLAR FRACTION	NET ADDED ENERGY MJ/m^3	TRADE-OFF m^2 collector/m^3 storage
SUB 50							
Standard	4500	14500	0.242	0.950	0.653	153	0.63
Passive	2400	8700	0.198	0.953	0.623	123	0.60
Superinsulated	1000	2800	0.183	0.957	0.726	103	0.50
SUB 50 - space heat only							
Standard*	3500	15750	0.266	0.950	0.574	150	0.55
Passive	1650	8000	0.198	0.950	0.470	130	0.60
Superinsulated	500	2100	0.156	0.950	0.453	125	0.63
SUB 1							
Standard	120	300	0.182	0.95	0.730	112	0.55
Passive	65	185	0.160	0.952	0.676	100	0.55
Superinsulated	30	55	0.122	0.955	0.804	70	0.50
TUB 50							
Standard	2300	6500	0.235	0.948	0.685	150	0.67
Passive	1500	3600	0.186	0.956	0.743	113	0.70
Superinsulated	770	1520	0.176	0.961	0.810	100	0.70
HUB 200							
Standard	5000	16000	0.248	0.948	0.671	146	0.60
Conserving	2200	5700	0.201	0.955	0.741	115	0.63

*System with collector tilt equal to latitude.

SIMULATION RESULTS
BISMARCK, N. DAK.
Evacuated-Tube Collector - Single-Tank System

LOAD TYPE	COLLECTOR AREA (m^2)	STORAGE VOLUME (m^3)	EFFICIENCY	SOLAR FRACTION	DIURNAL SOLAR FRACTION	NET ADDED ENERGY MJ/m^3	TRADE-OFF m^2 collector/m^3 storage
SUB 50							
Standard	4000	13500	0.272	0.933	0.648	160	0.36
Passive	1800	7200	0.251	0.922	0.597	145	0.45
Superinsulated	700	2150	0.241	0.910	0.694	122	0.43
SUB 50 - space heat only							
Standard*	3500	13000	0.274	0.950	0.606	168	0.42
Passive	1300	6500	0.246	0.950	0.449	165	0.63
Superinsulated	360	1800	0.224	0.950	0.434	150	0.63
SUB 1							
Standard	95	280	0.230	0.935	0.706	123	0.39
Passive	40	165	0.210	0.923	0.632	110	0.42
Superinsulated	20	48	0.174	0.906	0.783	65	0.25
TUB 50							
Standard	2000	5900	0.268	0.920	0.693	143	0.39
Passive	1050	3100	0.254	0.912	0.711	115	0.42
Superinsulated	550	1200	0.238	0.910	0.801	85	0.25
HUB 200							
Standard	4400	14000	0.276	0.923	0.664	155	0.35
Conserving	1600	4500	0.260	0.893	0.714	120	0.60

*System with collector tilt equal to latitude.

SIMULATION RESULTS
BISMARCK, N. DAK.
Evacuated-Tube Collector – Two-Tank System

LOAD TYPE	COLLECTOR AREA (m^2)	STORAGE VOLUME (m^3)	EFFICIENCY	SOLAR FRACTION	DIURNAL SOLAR FRACTION	NET ADDED ENERGY MJ/m^3	TRADE-OFF m^2 collector/m^3 storage
SUB 50							
Standard	3500	12250	0.310	0.945	0.610	200	0.42
Passive	1800	6400	0.282	0.948	0.615	170	0.43
Superinsulated	700	2100	0.260	0.948	0.710	140	0.39
SUB 50 - space heat only							
Standard*	3000	12800	0.308	0.950	0.561	190	0.37
Passive	1300	6200	0.252	0.950	0.474	160	0.50
Superinsulated	320	1900	0.232	0.950	0.442	140	0.43
SUB 1							
Standard	90	260	0.248	0.947	0.694	145	0.36
Passive	40	160	0.222	0.948	0.664	115	0.39
Superinsulated	19	40	0.200	0.950	0.788	105	0.35
TUB 50							
Standard	1800	5400	0.301	0.944	0.664	195	0.40
Passive	1000	3000	0.272	0.944	0.714	145	0.36
Superinsulated	530	1060	0.258	0.950	0.817	125	0.36
HUB 200							
Standard	4000	13000	0.308	0.942	0.641	195	0.63
Conserving	1600	4200	0.260	0.944	0.730	155	0.40

*System with collector tilt equal to latitude.

SIMULATION RESULTS
ALBUQUERQUE, N. MEX.
Flat-Plate Collector - Single-Tank System

LOAD TYPE	COLLECTOR AREA (m^2)	STORAGE VOLUME (m^3)	EFFICIENCY	SOLAR FRACTION	DIURNAL SOLAR FRACTION	NET ADDED ENERGY MJ/m^3	TRADE-OFF m^2 collector/m^3 storage
SUB 50							
Standard	1300	6200	0.323	0.920	0.729	123	0.17
Passive	450	680	0.263	0.908	0.836	42	0.25
Superinsulated	550	1900	0.285	0.908	0.760	95	0.14
SUB 50 - space heat only							
Standard*	1000	7000	0.333	0.949	0.636	140	0.17
SUB 1							
Standard	32	116	0.259	0.923	0.806	82	0.13
Semipassive	14	31	0.218	0.908	0.823	65	0.25
TUB 50							
Standard	700	2300	0.306	0.901	0.798	100	0.14
Passive	450	180	0.238	0.950	0.936	150	
HUB 200							
Standard	1550	6400	0.318	0.908	0.769	105	0.13
Conserving	750	1300	0.272	0.902	0.849	85	0.13

*System with collector tilt equal to latitude.

SIMULATION RESULTS
ALBUQUERQUE, N. MEX.
Flat-Plate Collector - Two-Tank System

LOAD TYPE	COLLECTOR AREA (m^2)	STORAGE VOLUME (m^3)	EFFICIENCY	SOLAR FRACTION	DIURNAL SOLAR FRACTION	NET ADDED ENERGY MJ/m^3	TRADE-OFF m^2 collector/m^3 storage
SUB 50							
Standard	1200	5850	0.354	0.942	0.704	165	0.14
Passive	475	960	0.265	0.958	0.888	120	0.22
Semipassive	530	1900	0.298	0.947	0.791	100	0.22
SUB 50 - space heat only							
Standard*	900	6300	0.375	0.950	0.647	150	0.19
SUB 1							
Standard	30	108	0.297	0.945	0.790	120	0.15
Semipassive	14	32	0.227	0.947	0.857	70	0.17
TUB 50							
Standard	680	2150	0.334	0.940	0.797	150	0.18
Passive	400	320	0.270	0.961	0.944	70	0.25
HUB 200							
Standard	1500	6000	0.344	0.944	0.762	150	0.17
Conserving	720	1500	0.300	0.946	0.864	110	0.21

*System with collector tilt equal to latitude.

SIMULATION RESULTS
ALBUQUERQUE, N. MEX.
Evacuated-Tube Collector - Single-Tank System

LOAD TYPE	COLLECTOR AREA (m^2)	STORAGE VOLUME (m^3)	EFFICIENCY	SOLAR FRACTION	DIURNAL SOLAR FRACTION	NET ADDED ENERGY MJ/m^3	TRADE-OFF m^2 collector/m^3 storage
SUB 50							
Standard	1300	6400	0.316	0.924	0.653	170	0.14
Passive	400	880	0.292	0.896	0.808	160	0.18
Semipassive	500	2100	0.299	0.894	0.697	115	0.20
SUB 50 - space heat only							
Standard*	1050	6400	0.316	0.950	0.567	190	0.21
SUB 1							
Standard	32	120	0.260	0.923	0.731	130	0.15
Semipassive	13	35	0.234	0.900	0.775	90	0.18
TUB 50							
Standard	700	2500	0.300	0.900	0.729	150	0.18
Passive	350	300	0.291	0.908	0.890	80	0.18
HUB 200							
Standard	1600	6400	0.310	0.914	0.706	160	0.18
Conserving	675	1700	0.301	0.890	0.792	115	0.17

*System with collector tilt equal to latitude.

SIMULATION RESULTS
ALBUQUERQUE, N. MEX.
Evacuated-Tube Collector - Two-Tank System

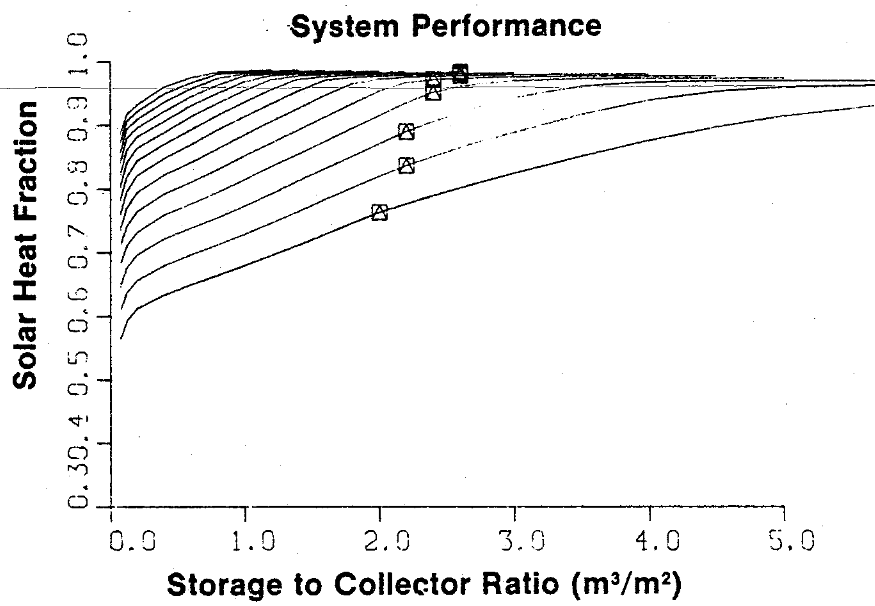
LOAD TYPE	COLLECTOR AREA (m^2)	STORAGE VOLUME (m^3)	EFFICIENCY	SOLAR FRACTION	DIURNAL SOLAR FRACTION	NET ADDED ENERGY MJ/m^3	TRADE-OFF m^2 collector/m^3 storage
SUB 50							
Standard*	1200	5800	0.340	0.943	0.631	215	0.22
Passive	420	980	0.304	0.959	0.841	190	0.23
Semipassive	500	1900	0.316	0.942	0.719	145	0.25
SUB 50 - space heat only							
Standard	950	6400	0.347	0.950	0.553	195	0.19
SUB 1							
Standard	29	120	0.293	0.941	0.703	160	0.18
Semipassive	13	36	0.259	0.945	0.786	125	0.20
TUB 50							
Standard	660	2300	0.338	0.936	0.716	205	0.20
Passive	350	420	0.307	0.955	0.904	140	0.25
HUB 200							
Standard	1500	6000	0.340	0.938	0.691	205	0.20
Conserving	650	1700	0.322	0.941	0.801	165	0.25

*System with collector tilt equal to latitude.

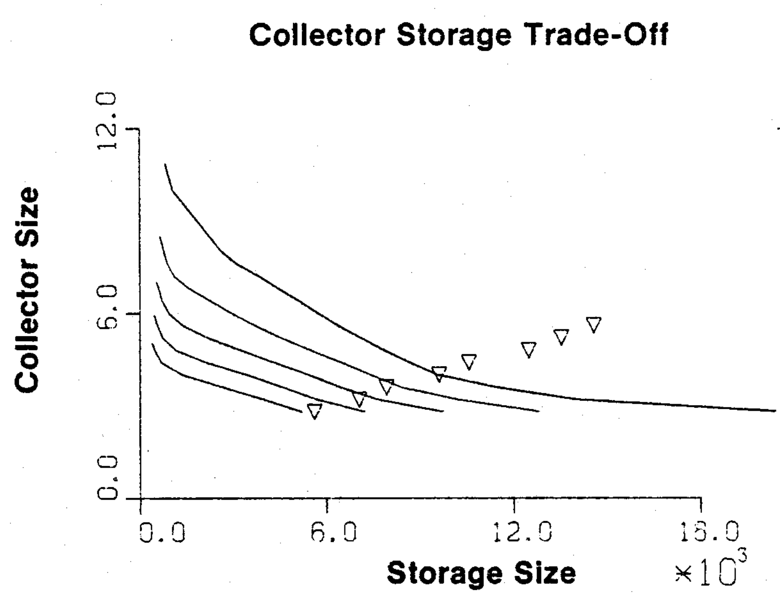
HOT WATER SYSTEMS

All systems presented here are to provide hot water only. The loads are all SUB 50 with the standard hot water load given for the city in Fig. A-2. Systems are all at the point of unconstrained operation. Collector tilt is equal to latitude plus 10 degree.

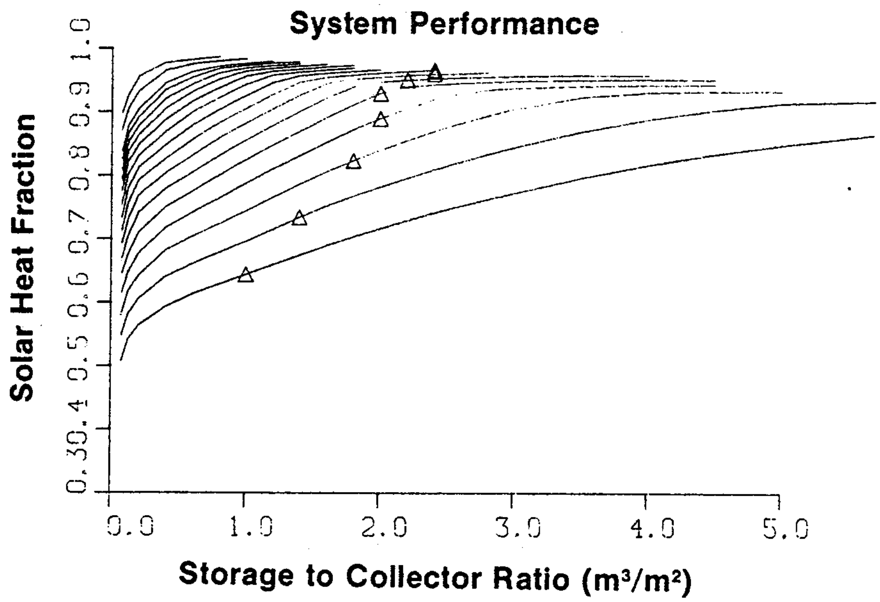
LOAD TYPE	COLLECTOR AREA (m^2)	STORAGE VOLUME (m^3)	EFFICIENCY	SOLAR FRACTION	DIURNAL SOLAR FRACTION	NET ADDED ENERGY MJ/m^3
Boston, Mass. Flat-plate collector						
Single-tank system	1000	400	0.164	0.938	0.935	13
Two-tank system	1000	600	0.170	0.974	0.956	40
Boston, Mass. Evacuated-tube collector						
Single-tank system	600	480	0.260	0.892	0.887	12
Two-tank system	600	480	0.273	0.937	0.906	70
Medford, Oreg. Flat-plate collector						
Single-tank system	600	960	0.204	0.894	0.854	39
Two-tank system	600	960	0.220	0.961	0.877	80
Medford, Oreg. Evacuated-tube collector						
Single-tank system	500	1000	0.249	0.907	0.847	54
Two-tank system	500	1000	0.265	0.964	0.868	86
Bismarck, N. Dak. Flat-plate collector						
Single-tank system	800	800	0.183	0.912	0.903	14
Two-tank system	800	800	0.193	0.960	0.914	70
Bismarck, N. Dak. Evacuated-tube collector						
Single-tank system	600	720	0.251	0.938	0.921	28
Two-tank system	600	720	0.262	0.978	0.935	70



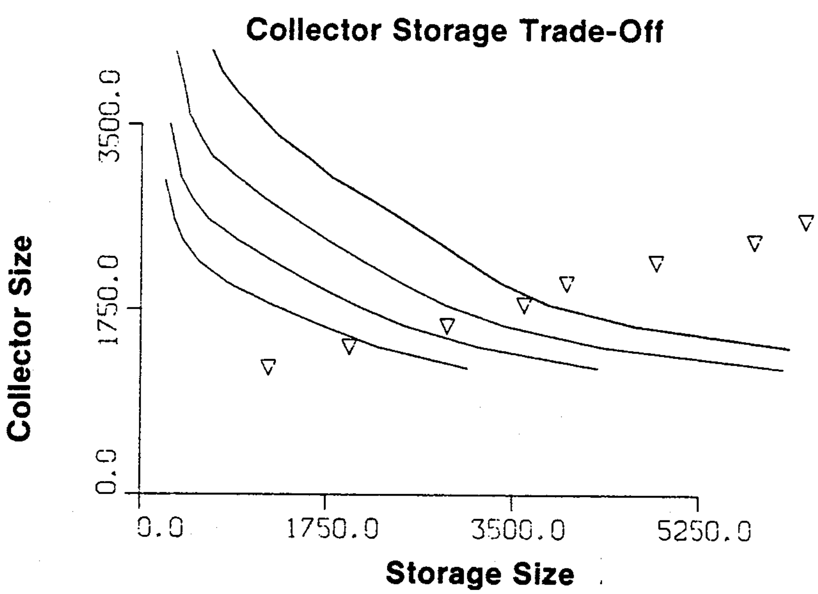
Collector sizes (m²): 2800, 3200, 3600, 4000, 4400, 4800, 5200, 5600, 6000, 6400. 6800, 7200, 7600, 8000



LOCATION: Boston, Mass.
LOAD TYPE: SUB-50, standard load, heat and hot water.
SYSTEM TYPE: Flat plate collector, single tank system.

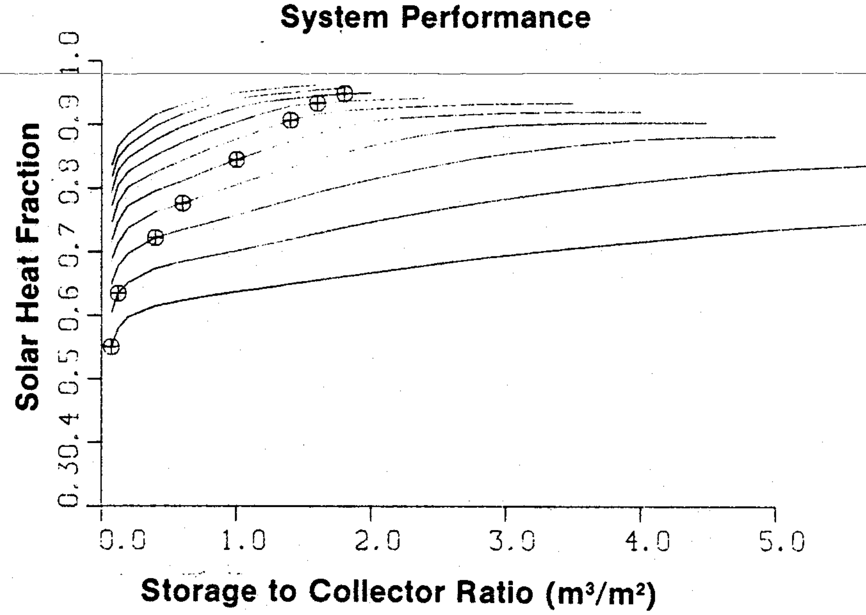


Collector sizes (m²): 1200, 1400, 1600, 1800, 2000, 2200, 2400, 2600, 2800, 3000, 3200. 3400, 3600, 4000, 4500, 5000.



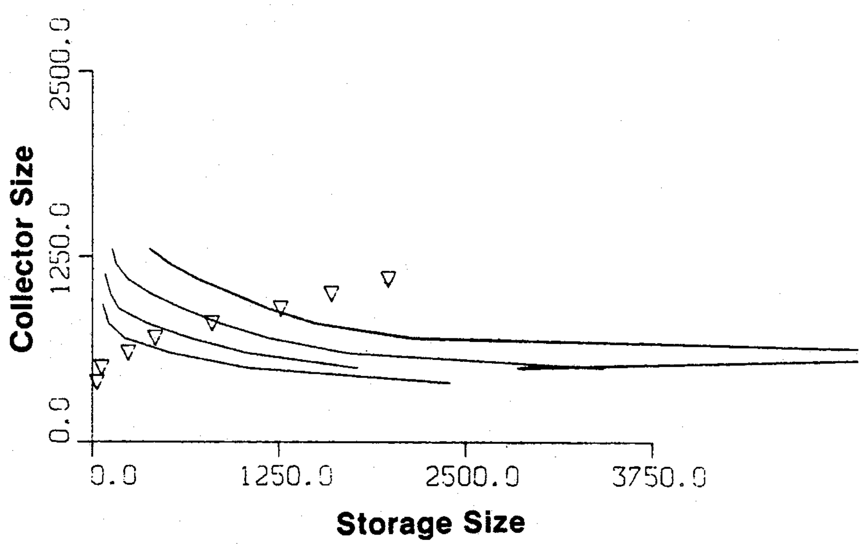
LOCATION: Boston, Mass.
LOAD TYPE: SUB-50, passive load, heat and hot water
SYSTEM TYPE: Flat plate collector, single tank system

System Performance

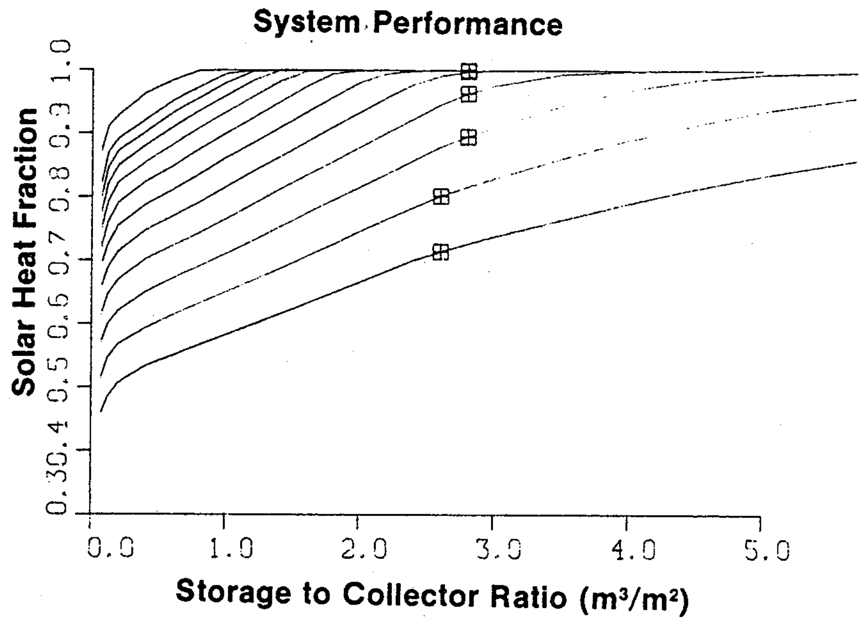


Collector sizes (m²): 400, 500, 600, 700, 800, 900, 1000, 1100,1200, 1300.

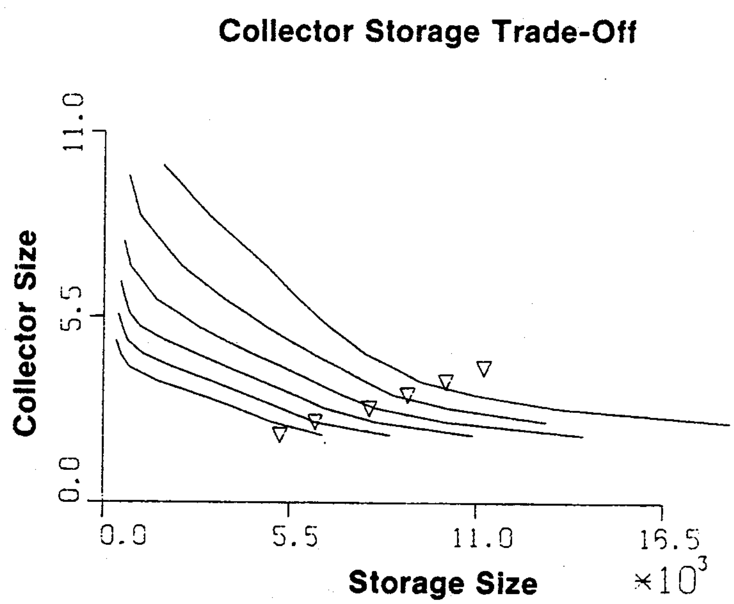
Collector Storage Trade-Off



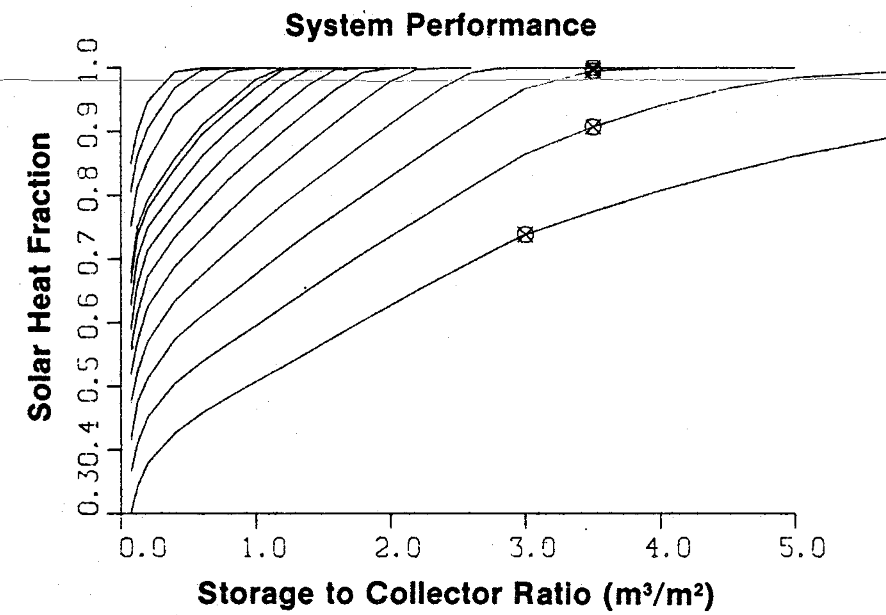
LOCATION: Boston, Mass.
LOAD TYPE: SUB-50, superinsulated load, heat and hot water.
SYSTEM TYPE: Flat plate collector, single tank system.



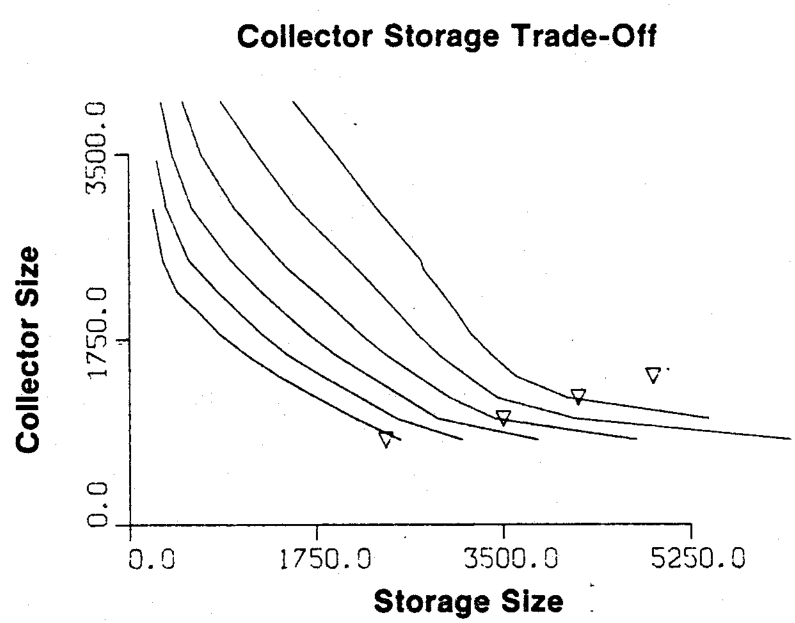
Collector sizes (m²): 2000, 2400, 2800, 3200, 3600, 4000, 4400, 4800, 5200, 5600, 6000, 7000.



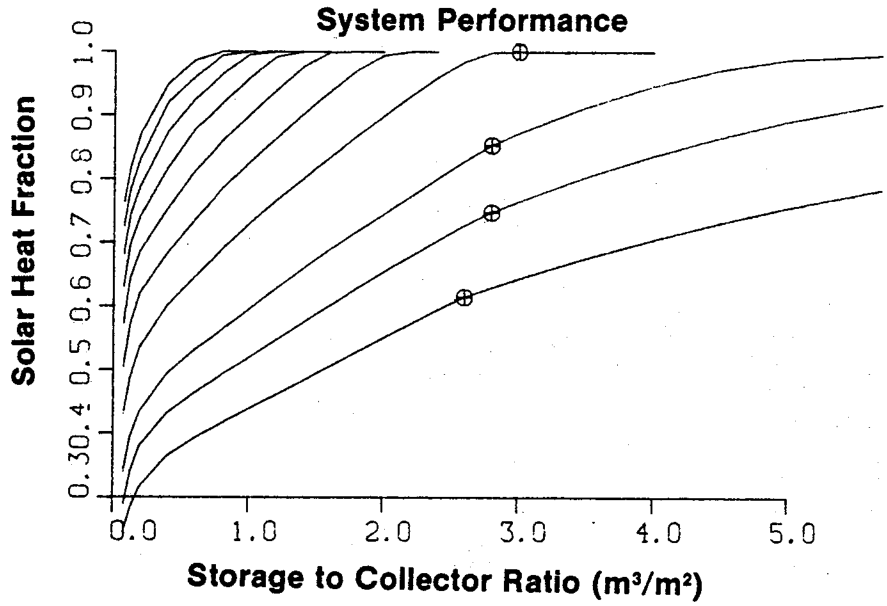
LOCATION: Boston, Mass.
LOAD TYPE: SUT-50, standard load, space heat only
SYSTEM TYPE: Flat-plate collector, single tank system



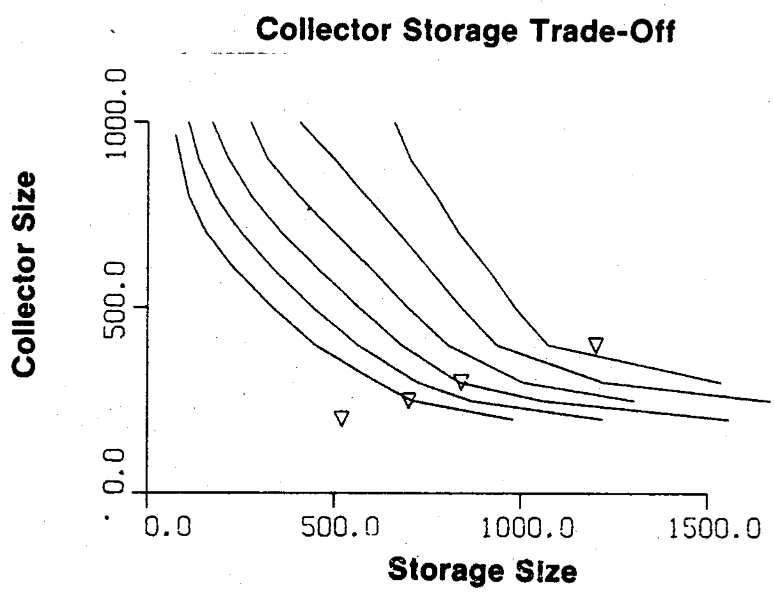
LOCATION: Boston, Mass.
LOAD TYPE: SUB-50, passive load, space heat only
SYSTEM TYPE: Flat-plate collector, single tank system.



SYSTEM TYPE: 800, 1000, 1200, 1400, 1600, 1800, 2000, 2200, 2400, 2500, 3000, 3500, 4000.

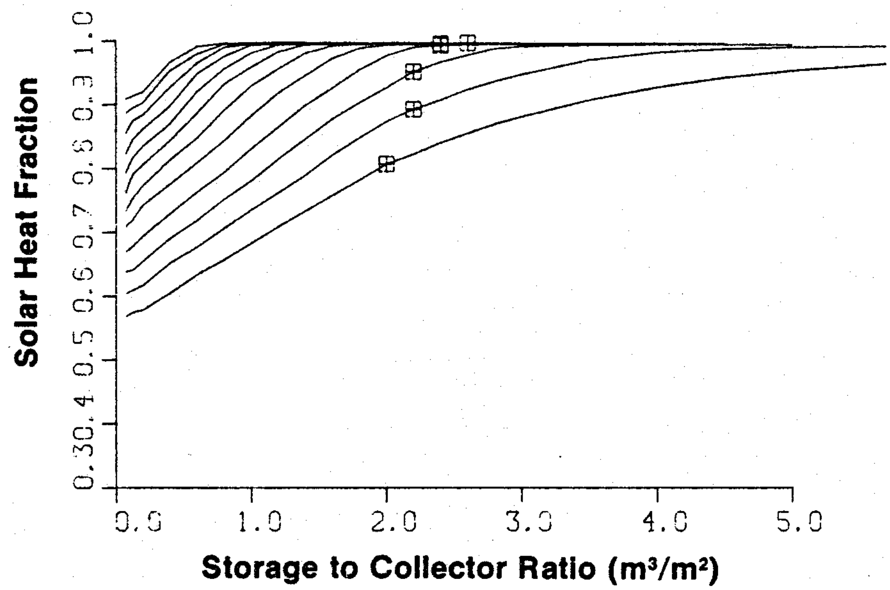


Collector sizes (m²): 200, 250, 300, 400, 500, 600, 700, 800, 900, 1000.



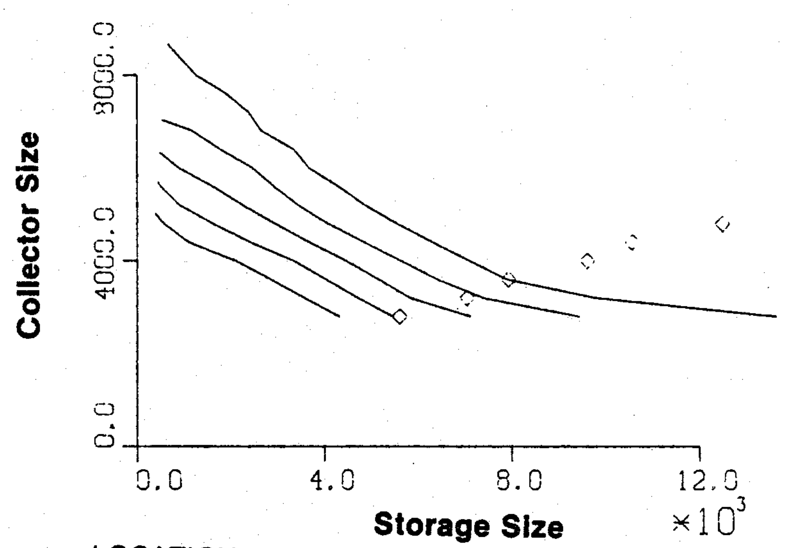
LOCATION: Boston, Mass.
LOAD TYPE: SUB-50, superinsulated load, space heat only
SYSTEM TYPE: Flat-plate collector, single tank system

System Performance

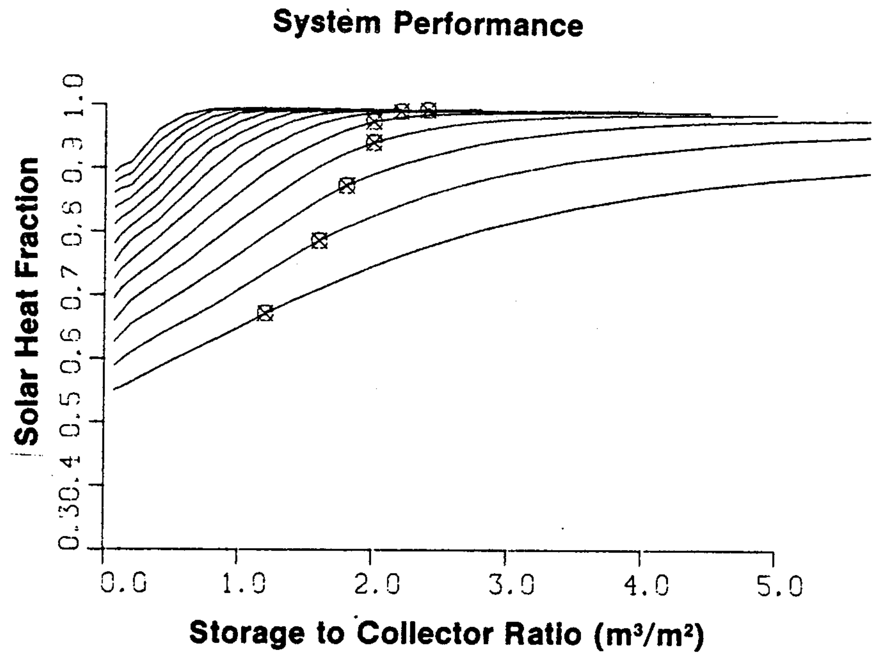


Collector sizes (m²): 2800, 3200, 3600, 4000, 4400, 4800, 5200, 5600, 6000, 6400, 6800, 7200.

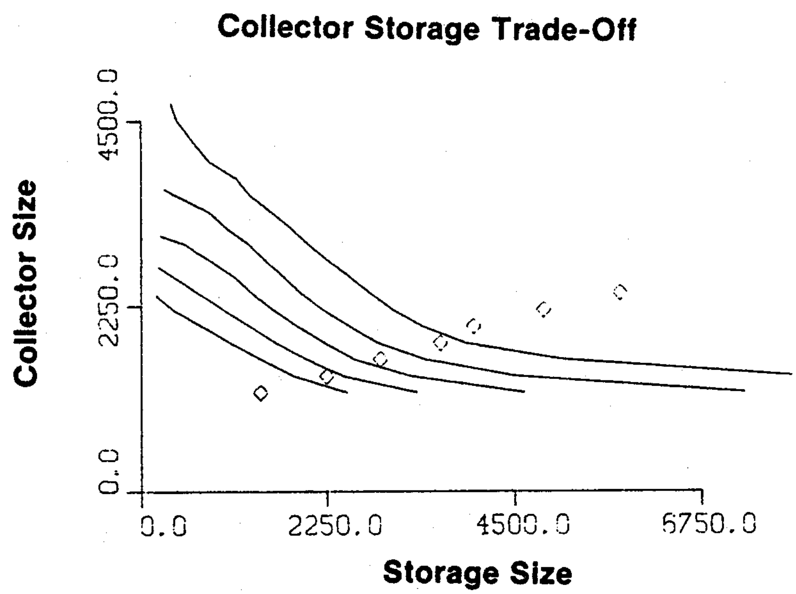
Collector Storage Trade-Off



LOCATION: Boston, Mass.
LOAD TYPE: SUB-50, standard load, heat and hot water
SYSTEM TYPE: Flat-plate collector, two-tank system.

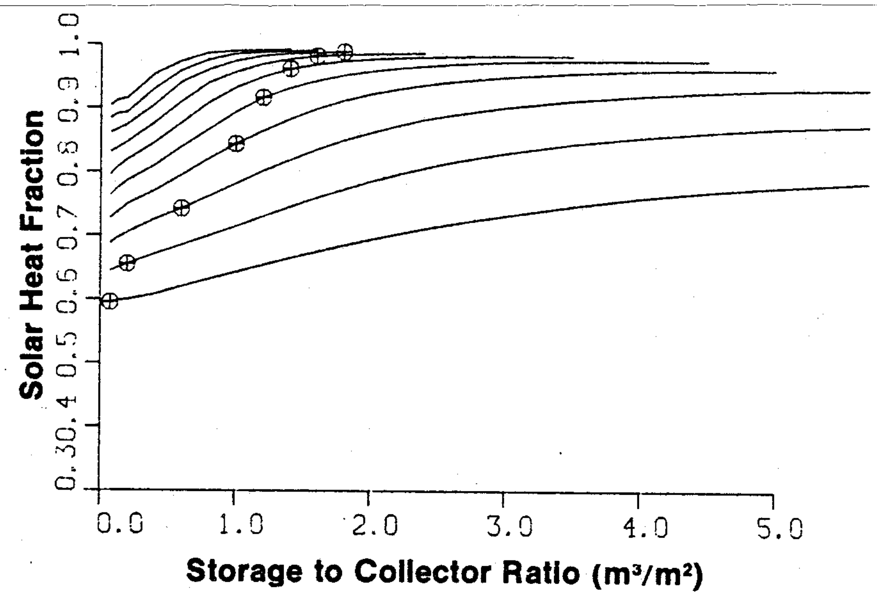


Collector sizes (m²): 1200, 1400, 1600, 1800, 2000, 2200, 2400, 2600, 2800, 3000, 3200, 3400, 3600.



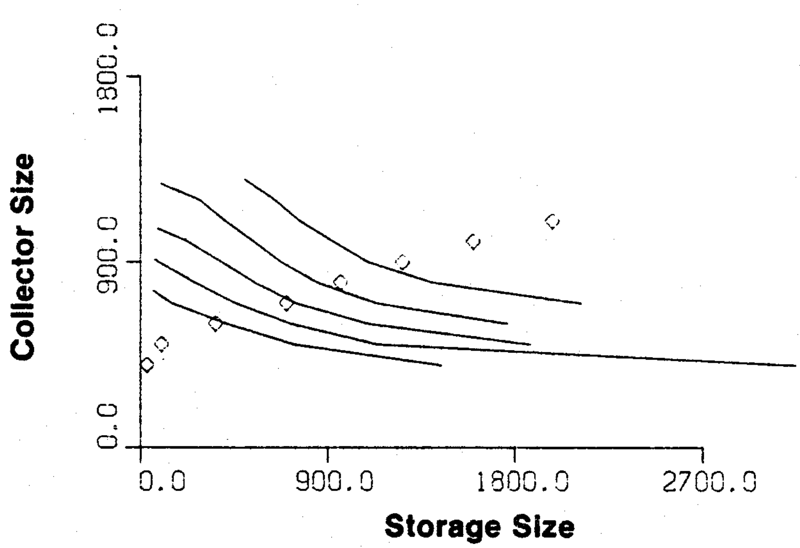
LOCATION: Boston, Mass.
LOAD TYPE: SUB-50, passive load, heat and hot water.
SYSTEM TYPE: Flat-plate collector, two-tank system.

System Performance



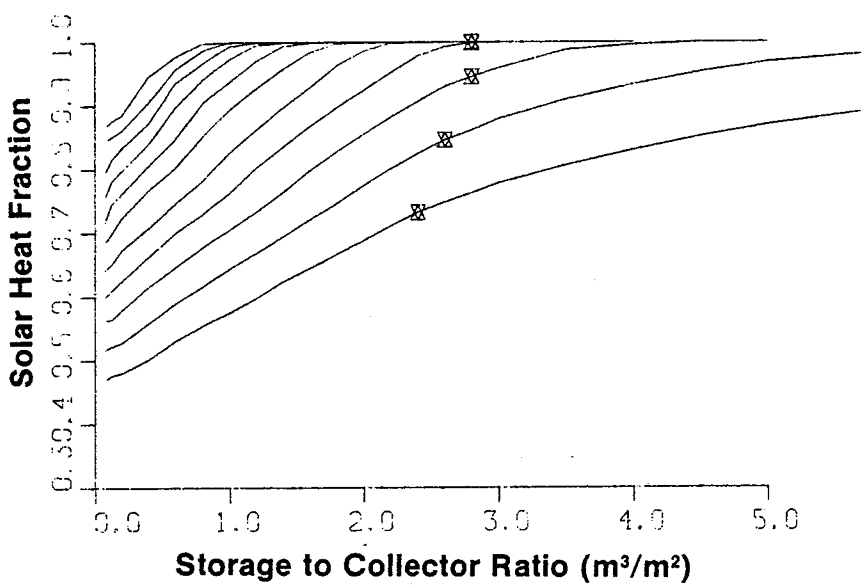
Collector sizes (m²): 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300.

Collector Storage Trade-Off



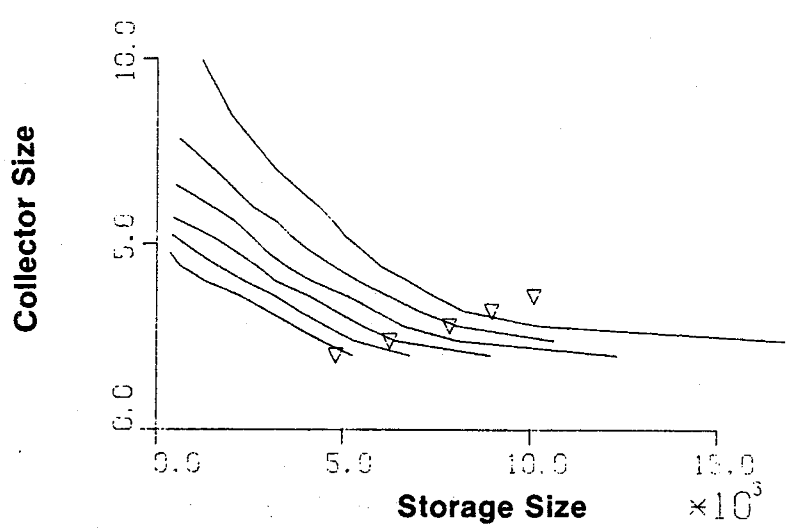
LOCATION: Boston, Mass.
LOAD TYPE: SUB-50, superinsulated load, heat and hot water.
SYSTEM TYPE: Flat-plate collector, two-tank system.

System Performance



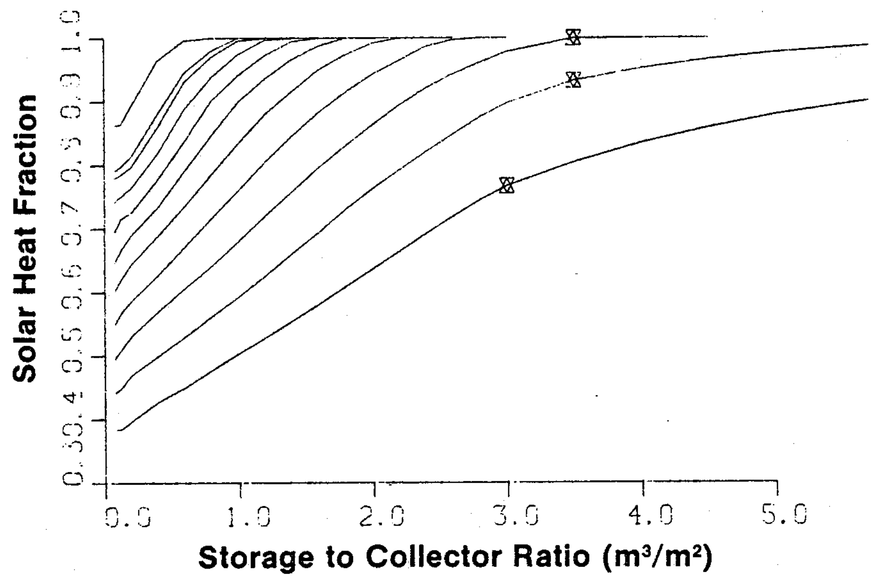
Collector sizes (m²): 2000, 2400, 2800, 3200, 3600, 4000, 4400, 4800, 5200, 5600, 6000.

Collector Storage Trade-Off



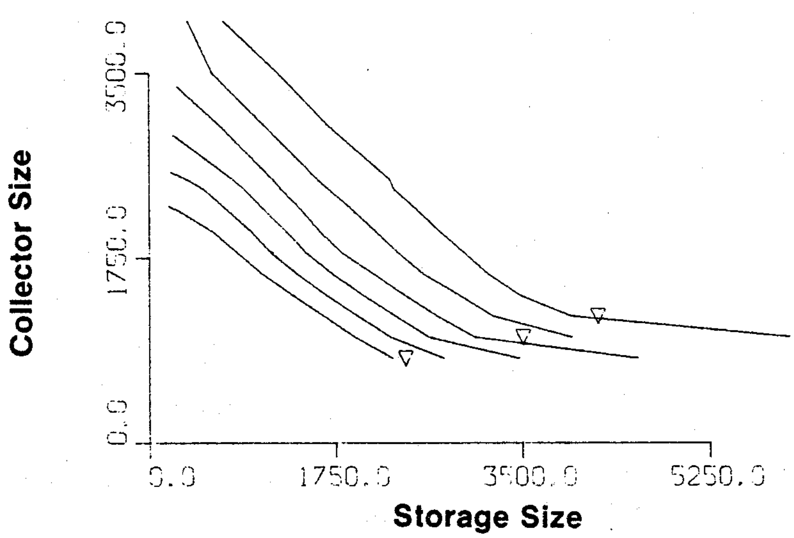
LOCATION: Boston, Mass.
LOAD TYPE: SUB-50, standard load, space heat only.
SYSTEM TYPE: Flat-plate collector, two-tank system.

System Performance



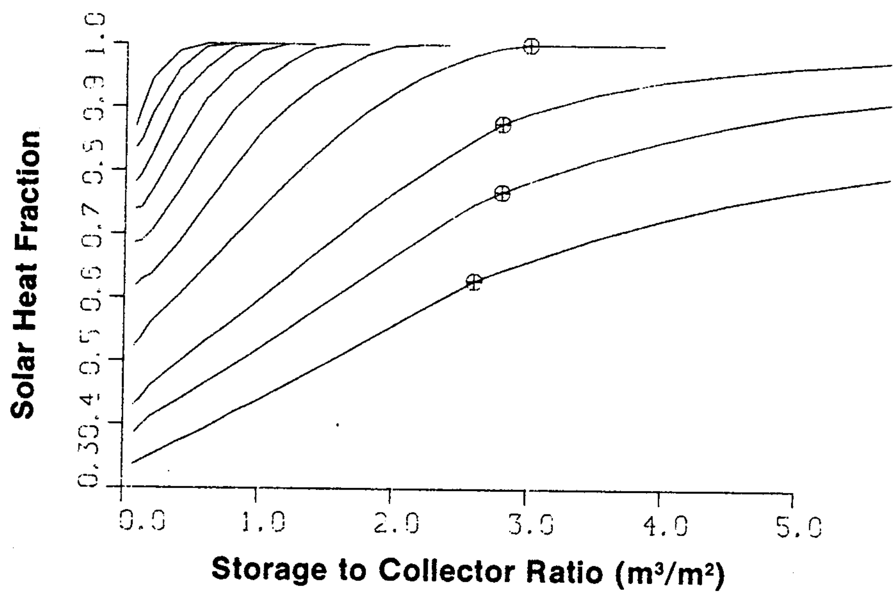
Collector sizes (m²): 800, 1000, 1200, 1400, 1600, 1800, 2000, 2200, 2400, 2500, 3000.

Collector Storage Trade-Off



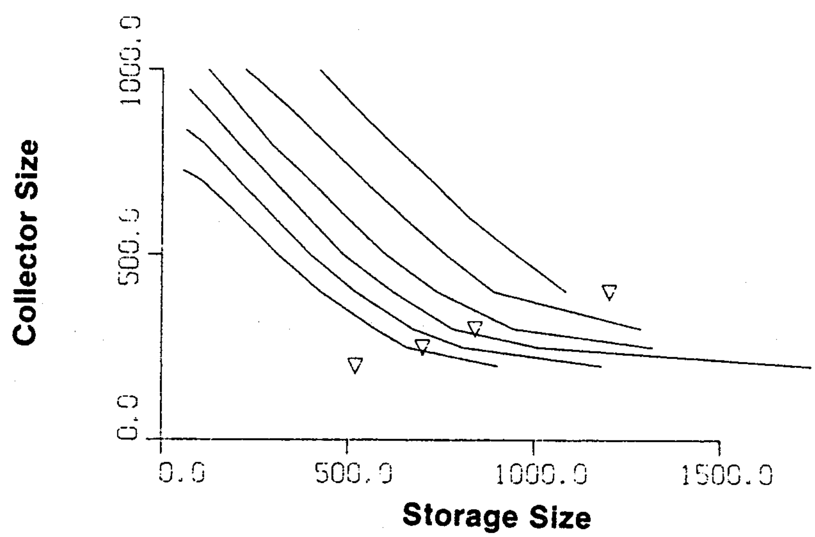
LOCATION: Boston, Mass.
LOAD TYPE: SUB-50, passive load, space heat only
SYSTEM TYPE: Flat-plate collector, two-tank system.

System Performance

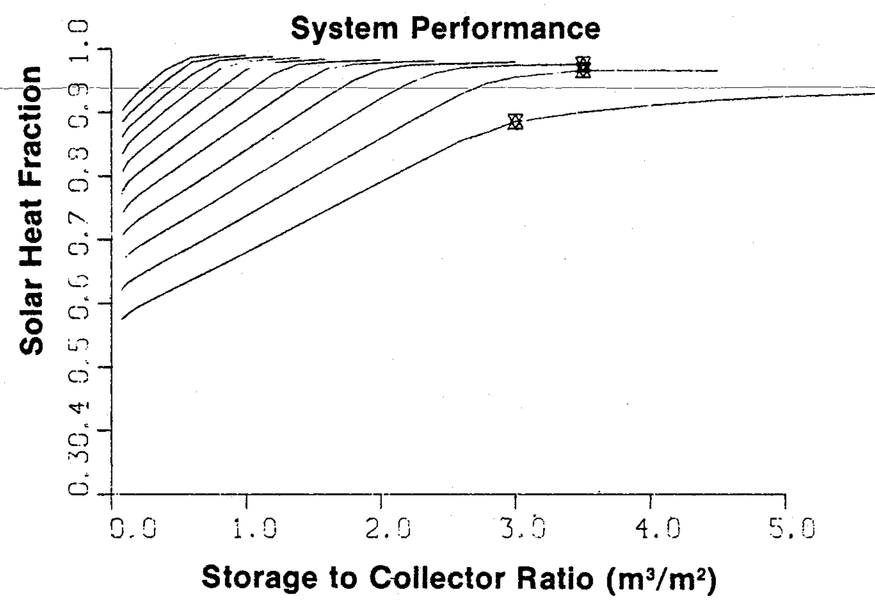


Collector sizes (m²): 200, 250, 300, 400, 500, 600, 700, 800, 900, 1000.

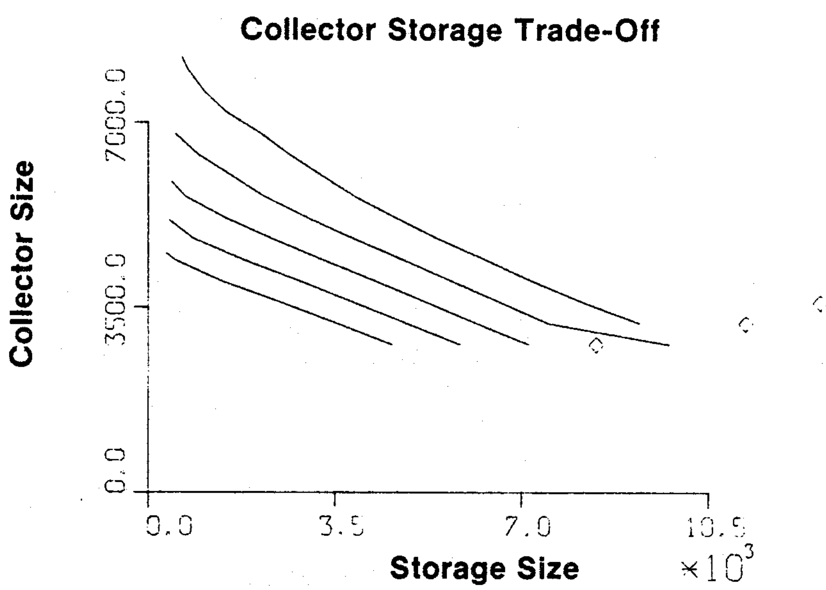
Collector Storage Trade-Off



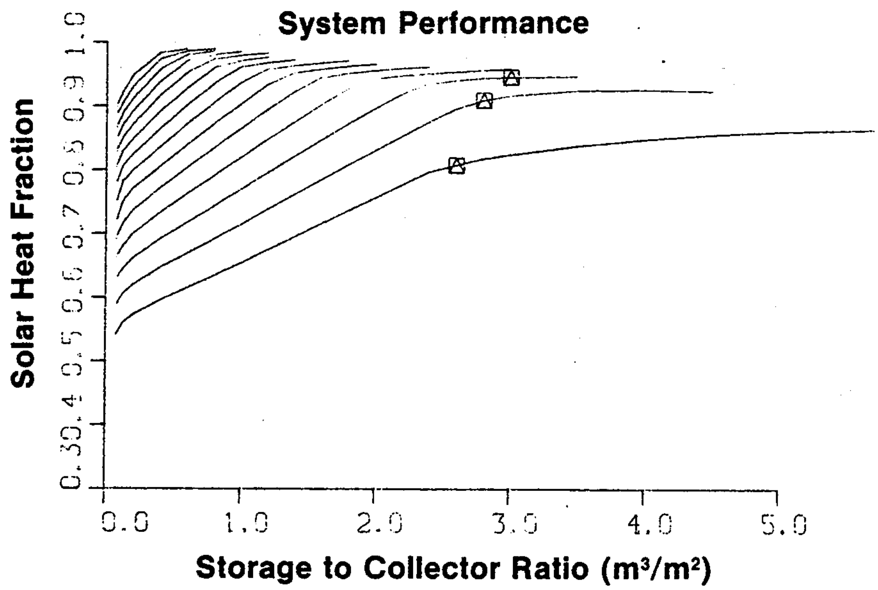
LOCATION: Boston, Mass.
LOAD TYPE: SUB-50, superinsulated load, space heat only.
SYSTEM TYPE: Flat-plate collector, two-tank system.



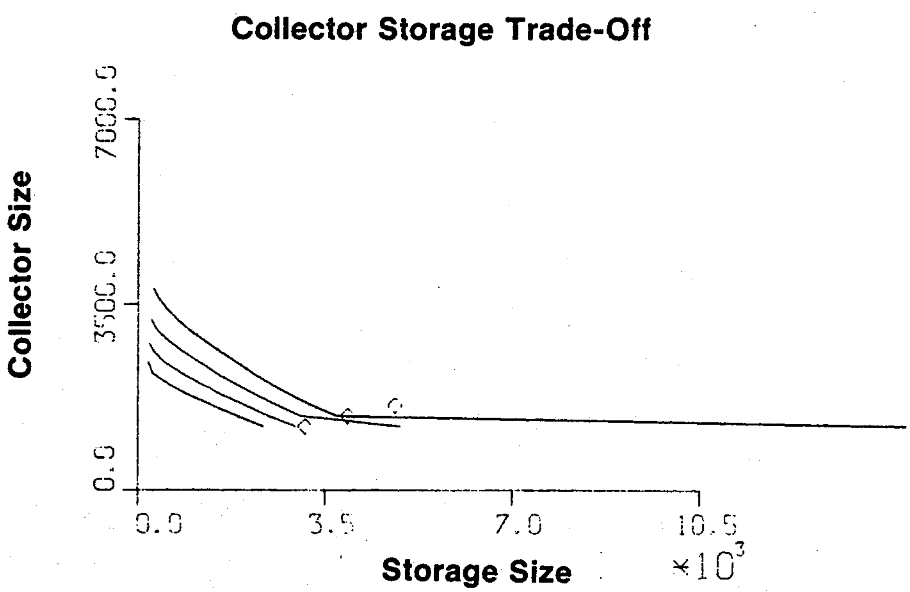
SYSTEM TYPE: 2800, 3200, 3600, 4000, 4400, 4800, 5200, 5600, 6000, 6400, 6800.



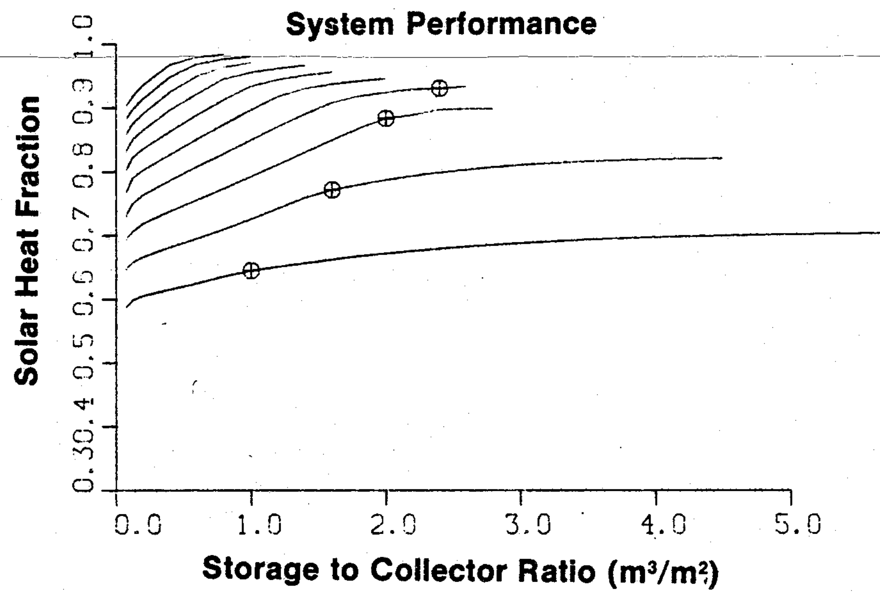
LOCATION: Boston, Mass.
LOAD TYPE: SUB-50, standard load, heat and hot water
SYSTEM TYPE: Evacuated tube collector, single tank system.



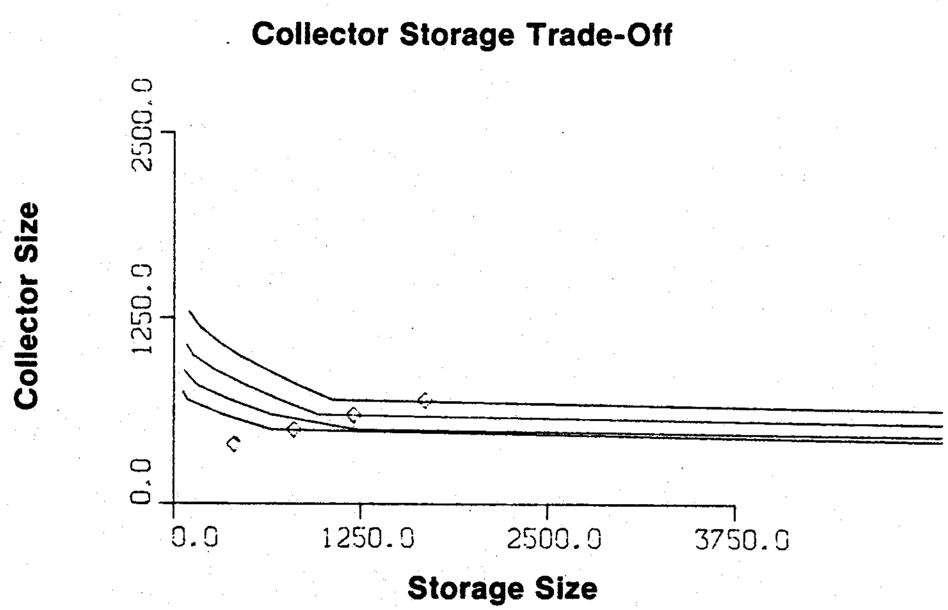
Collector sizes (m²): 1200, 1400, 1600, 1800, 2000, 2200, 2400, 2600, 2800, 3000, 3200, 3400, 3600, 3800.



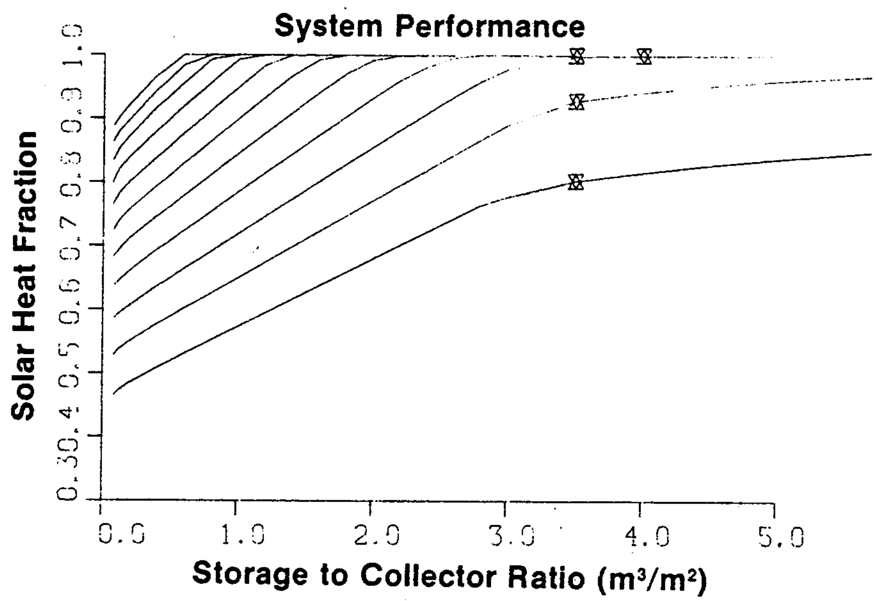
LOCATION: Boston, Mass.
LOAD TYPE: SUB-50, passive load, heat and hot water.
SYSTEM TYPE: Evacuated tube collector, single tank system.



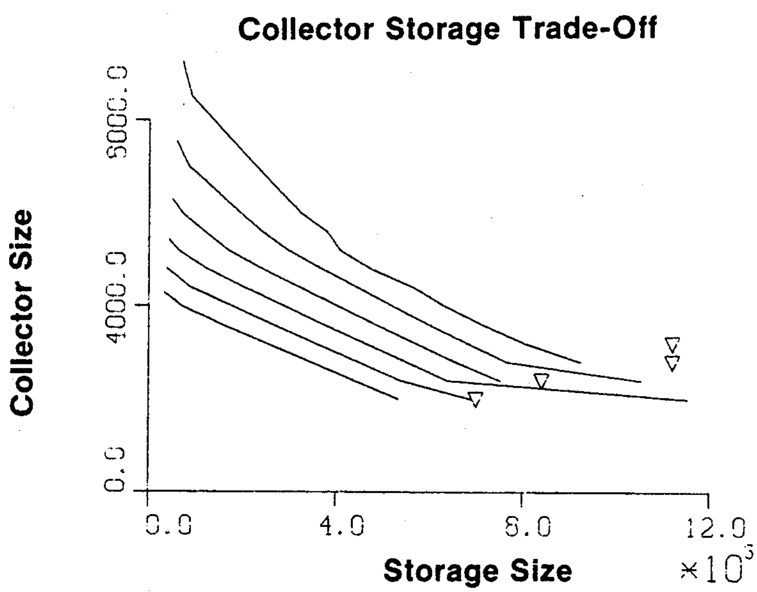
Collector sizes (m^2): 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300.



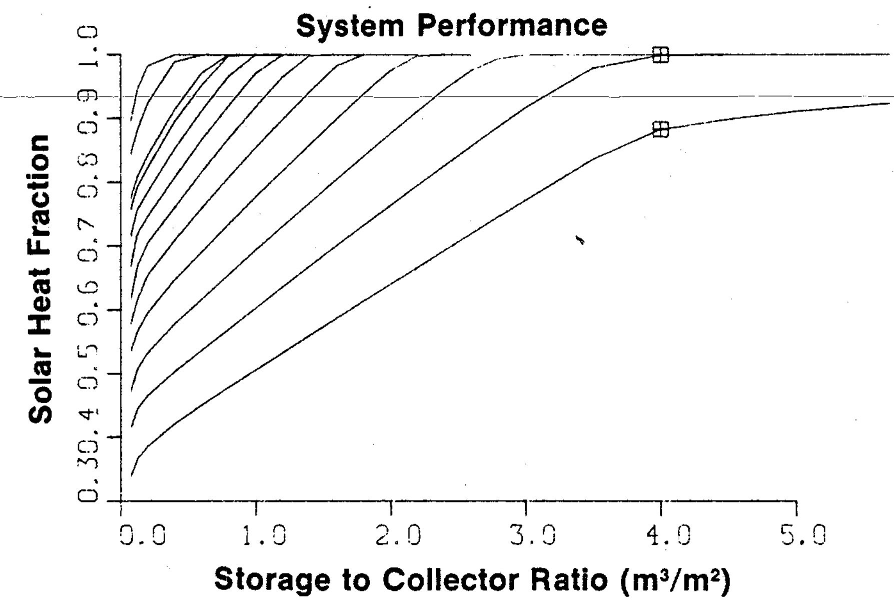
LOCATION: Boston, Mass.
LOAD TYPE: SUB-50, superinsulated load, heat and hot water
SYSTEM TYPE: Evacuated tube collector, two-tank system.



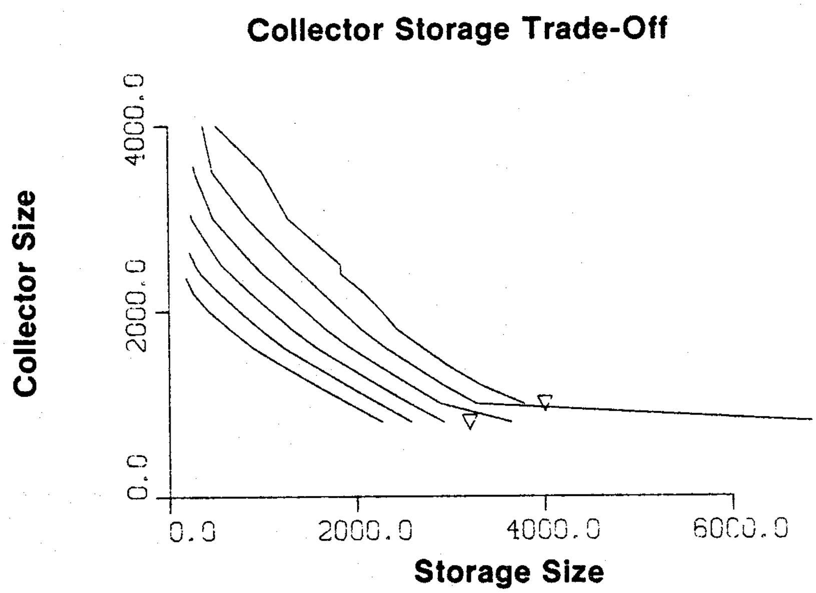
Collector sizes (m²): 2000, 2400, 2800, 3200, 3600, 4000, 4400, 4800, 5200, 5600, 6000.



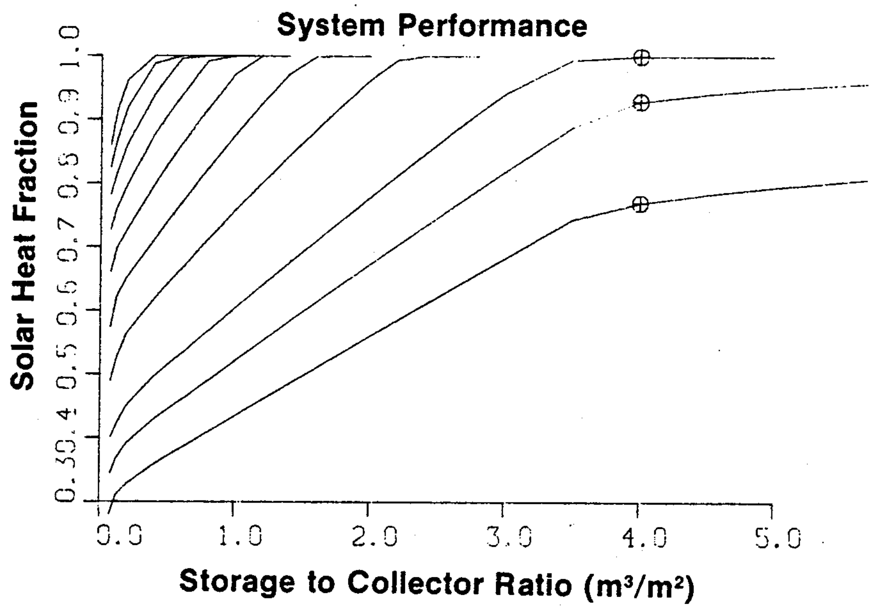
LOCATION: Boston, Mass.
LOAD TYPE: SUB-50, standard load, space heat only
SYSTEM TYPE: Evacuated tube collector, single tank system.



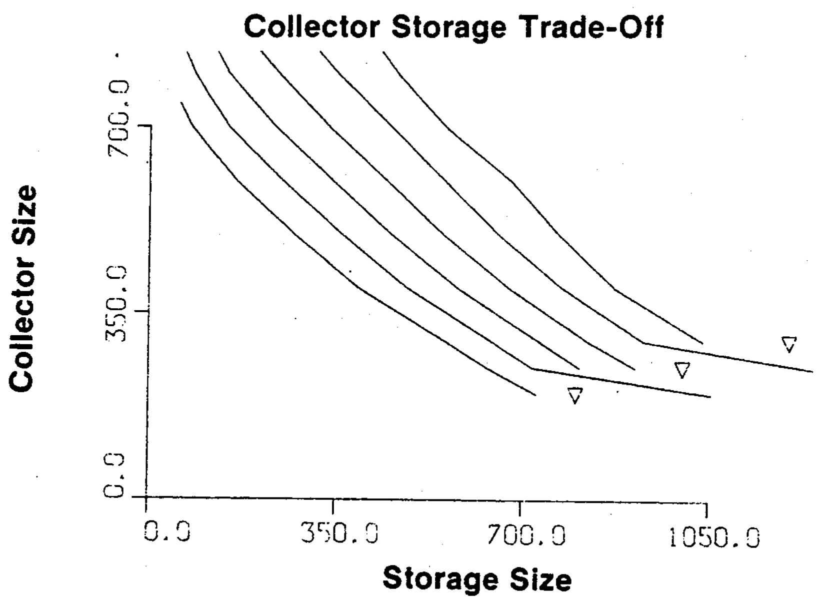
Collector sizes (m²): 800, 1000, 1200, 1400, 1600, 1800, 2000, 2200, 2400, 2500, 3000, 3500,



LOCATION: Boston, Mass.
LOAD TYPE: SUB-50, passive load, space heat only.
SYSTEM TYPE: Evacuated tube collector, single tank system

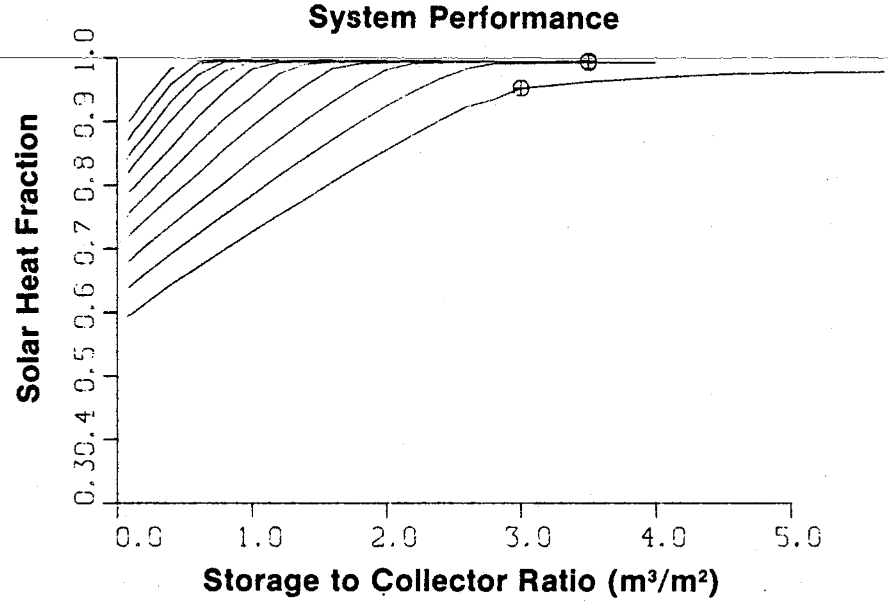


Collector sizes (m^2): 200, 250, 300, 400, 500, 600, 700, 800, 900, 1000.



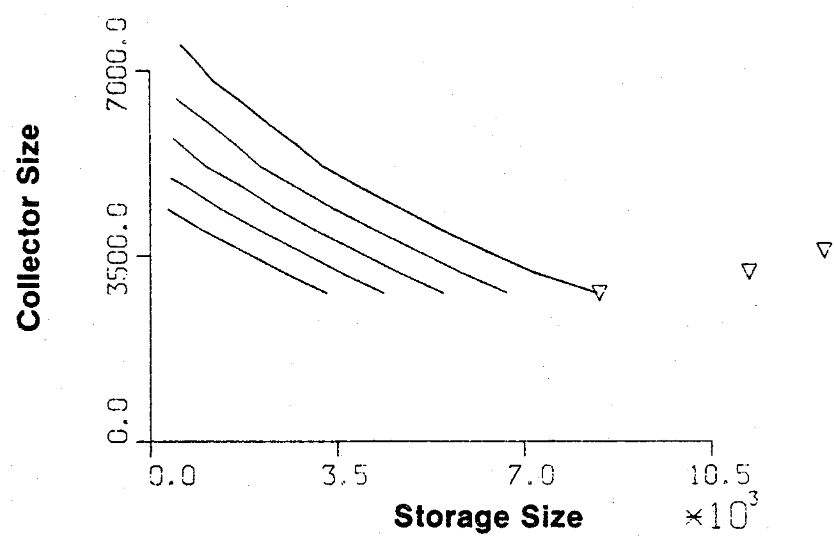
LOCATION: Boston, Mass.
LOAD TYPE: SUB-50, superinsulated load, space heat only.
SYSTEM TYPE: Evacuated tube collection, single-tank system.

System Performance

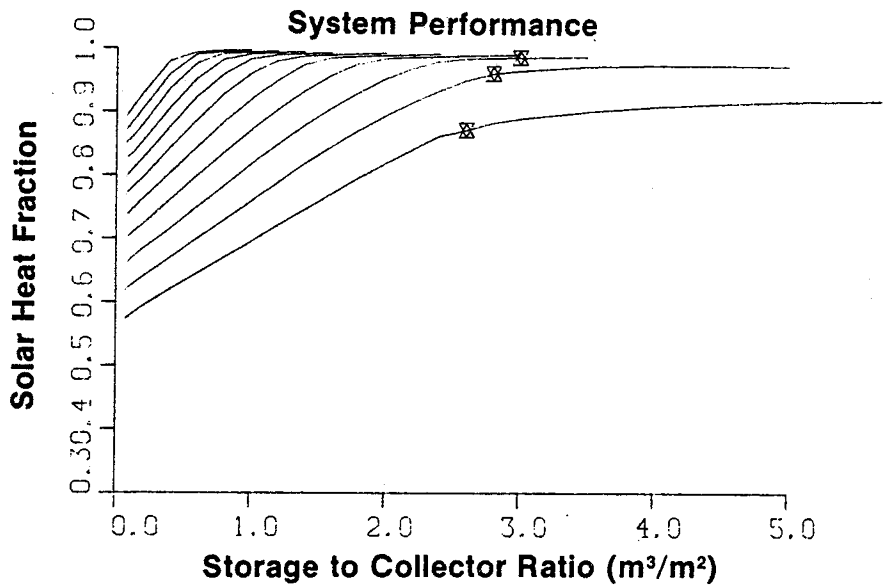


Collector sizes (m²): 2800, 3200, 3600, 400, 4400, 4800, 5200, 5600, 6000, 6400

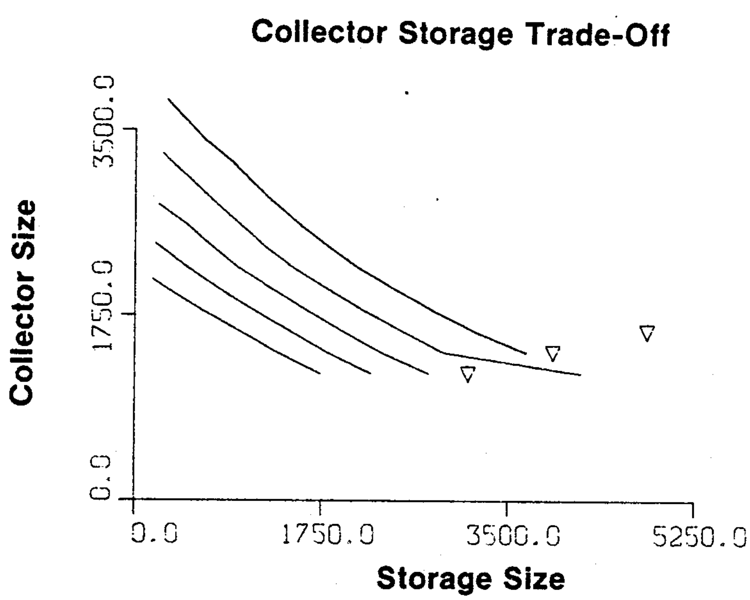
Collector Storage Trade-Off



LOCATION: Boston, Mass.
LOAD TYPE: SUB-50, standard load, heat and hot water
SYSTEM TYPE: Evacuated tube collection, two-tank system.



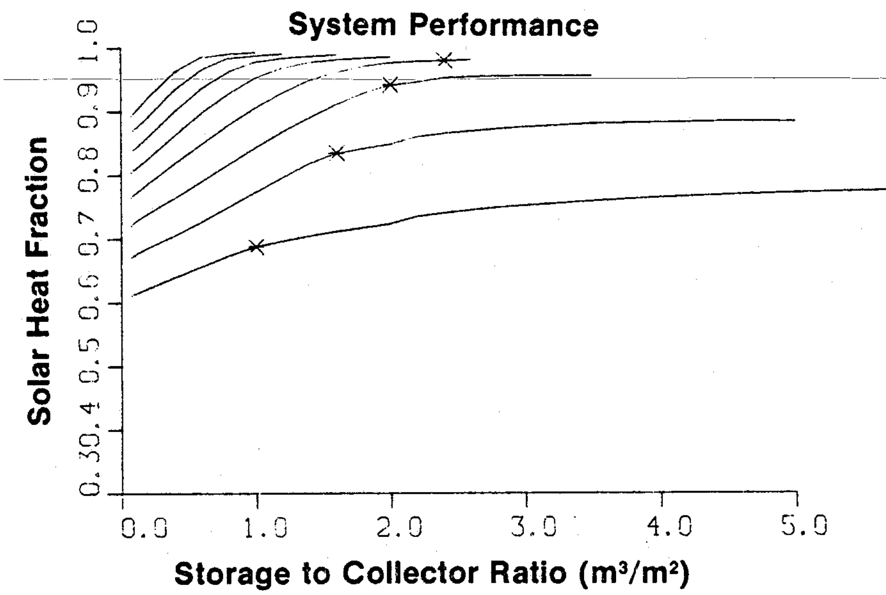
Collector sizes (m²): 1200, 1400, 1600, 1800, 2000, 2200, 2400, 2600, 2800, 3000, 3200



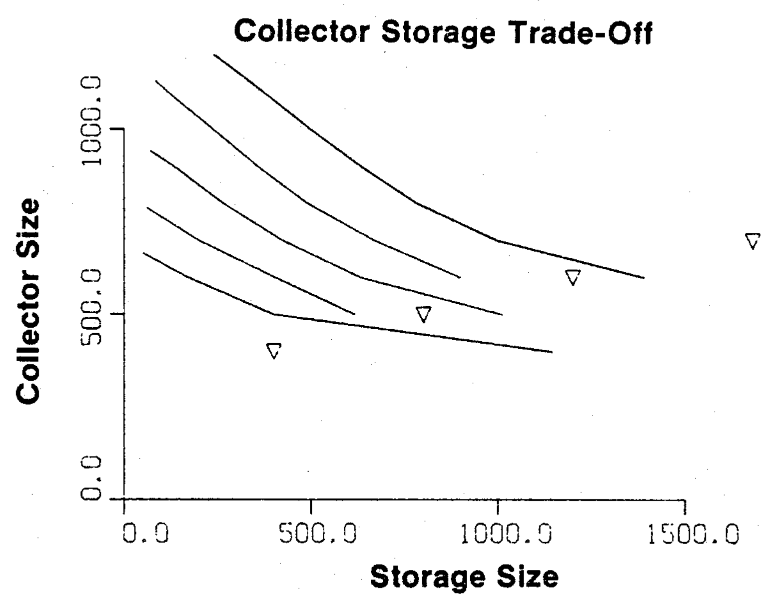
LOCATION: Boston, Mass.

LOAD TYPE: SUB-50 passive load, heat and hot water

SYSTEM TYPE: Evacuated tube collector, two-tank system.

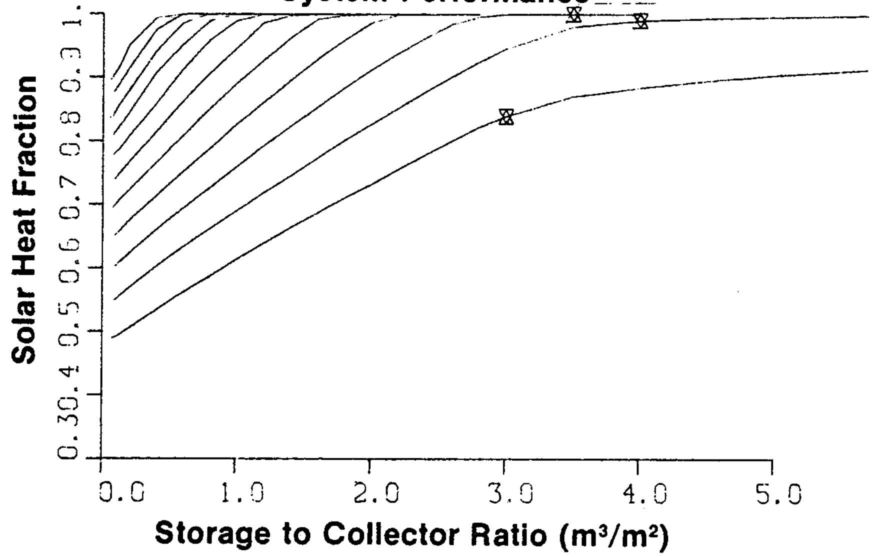


Collector sizes (m²): 400, 500, 600, 200, 800, 900, 1000, 1100,



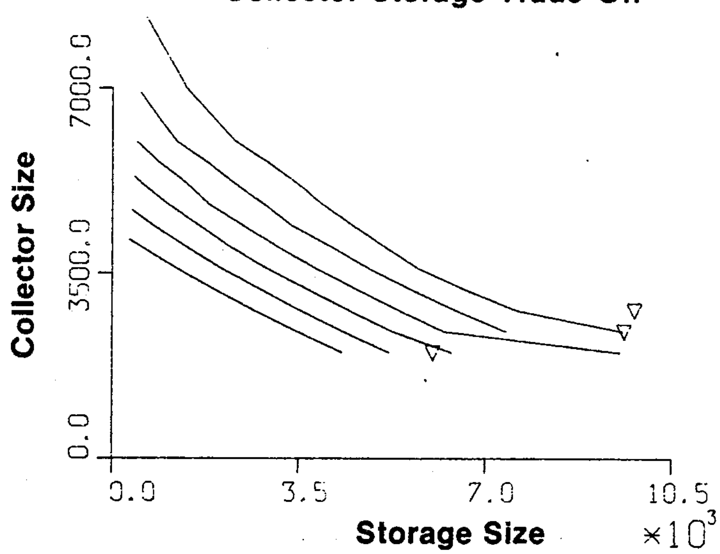
LOCATION: Boston, Mass.
LOAD TYPE: SUB-50, superinsulated load, heat and hot water.
SYSTEM TYPE: Evacuated tube collector, two-tank system.

System Performance

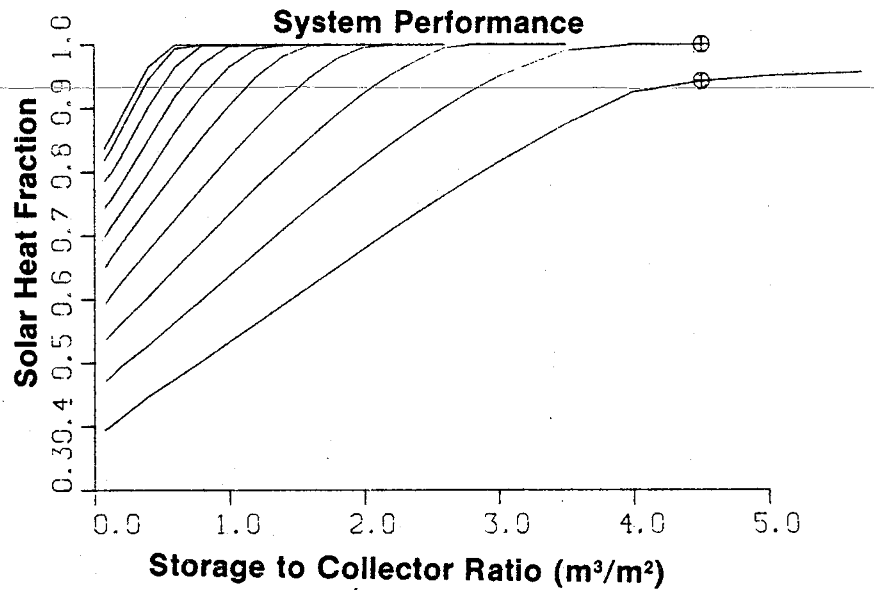


Collector sizes (m²): 2000, 2400, 2800, 3200, 3600, 4000, 4400, 4800, 5200, 5600, 6000.

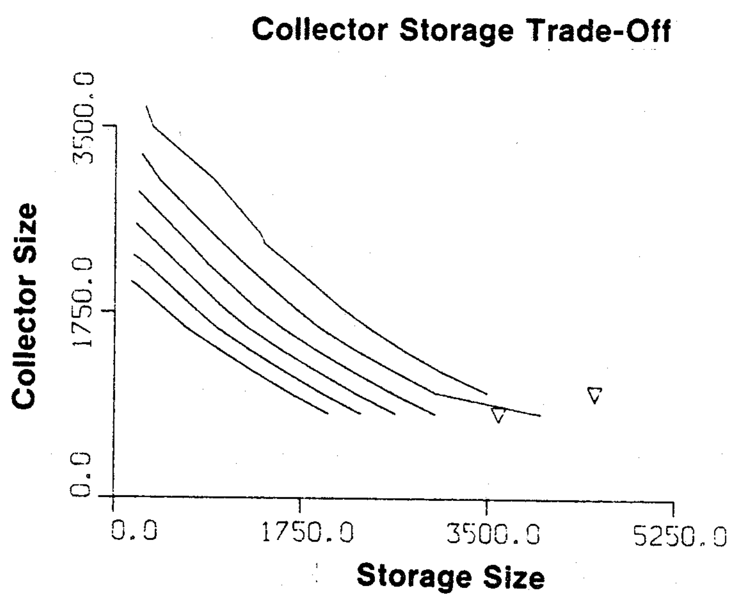
Collector Storage Trade-Off



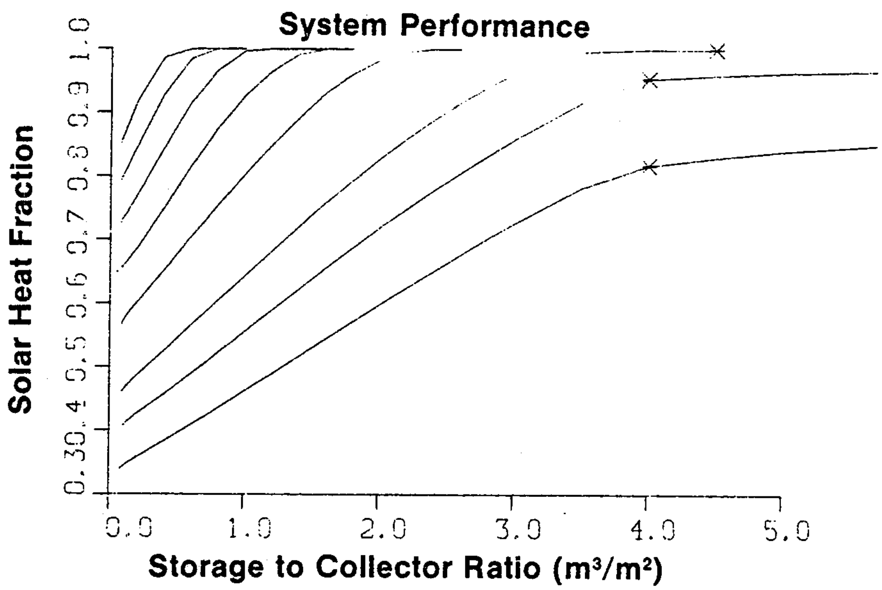
LOCATION: Boston, Mass.
LOAD TYPE: SUB-50, standard load, space heat only.
SYSTEM TYPE: Evacuated tube collector, two-tank system.



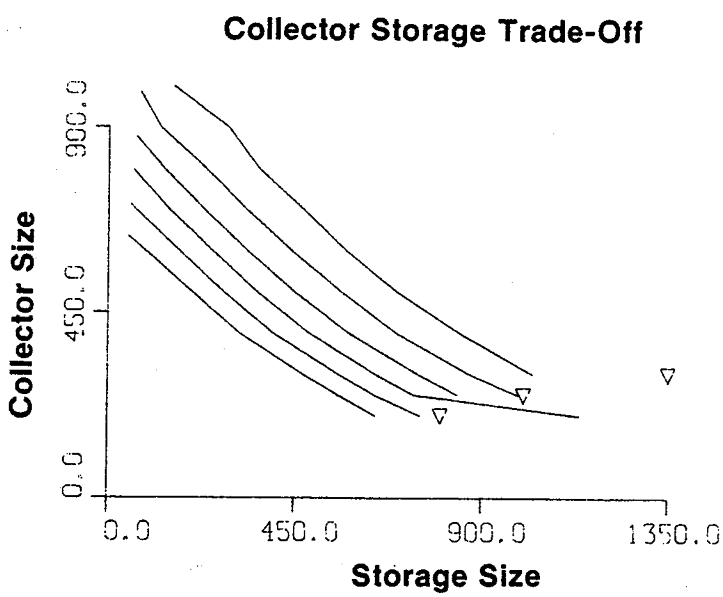
Collector sizes (m²): 800, 1000, 1200, 1400, 1600, 1800, 2000, 2200, 2400, 2500.



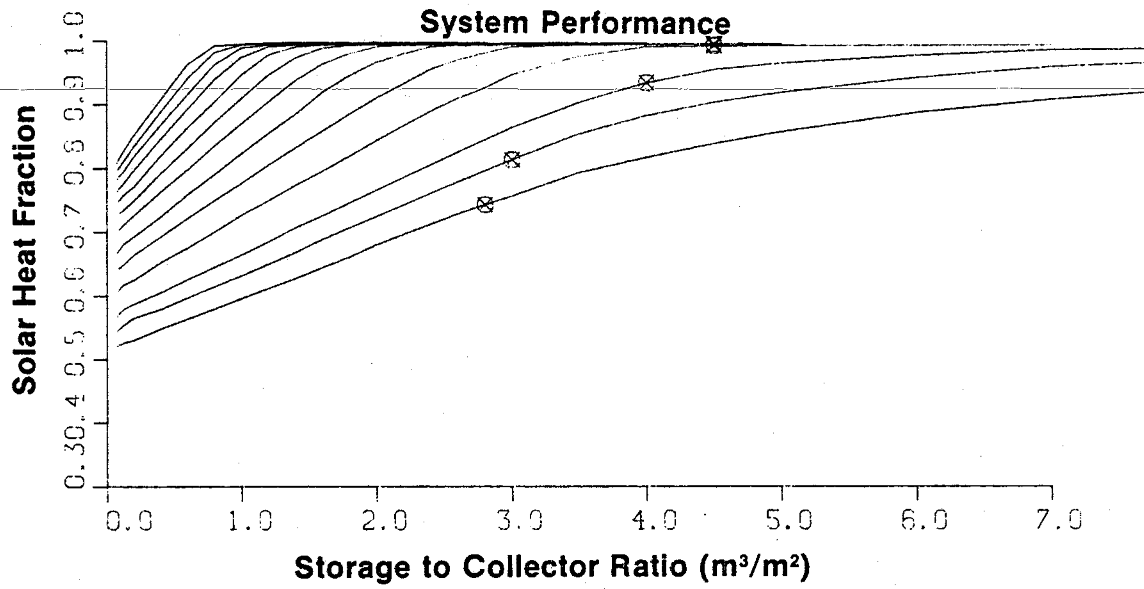
LOCATION: Boston, Mass.
LOAD TYPE: SUB-50 passsive load, space heat only.
SYSTEM TYPE: Evacuated tube collector, two-tank system.



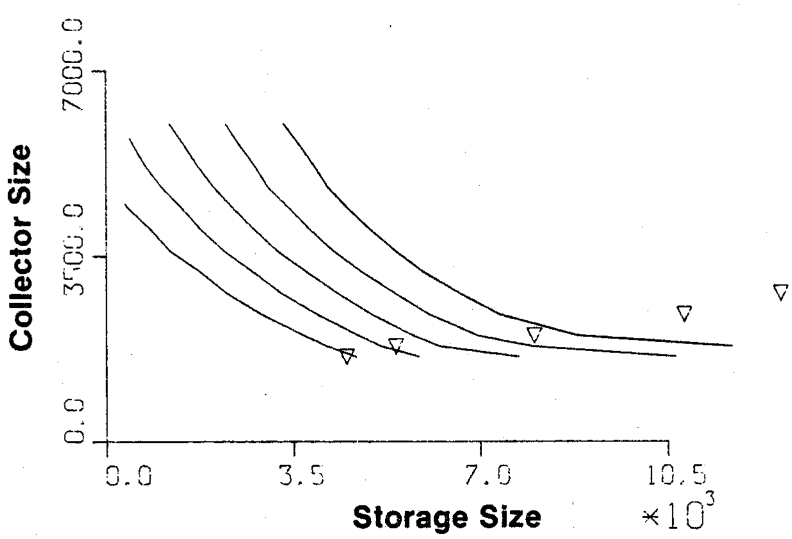
Collector sizes (m²): 200, 250, 300, 400, 500, 600, 700, 800.



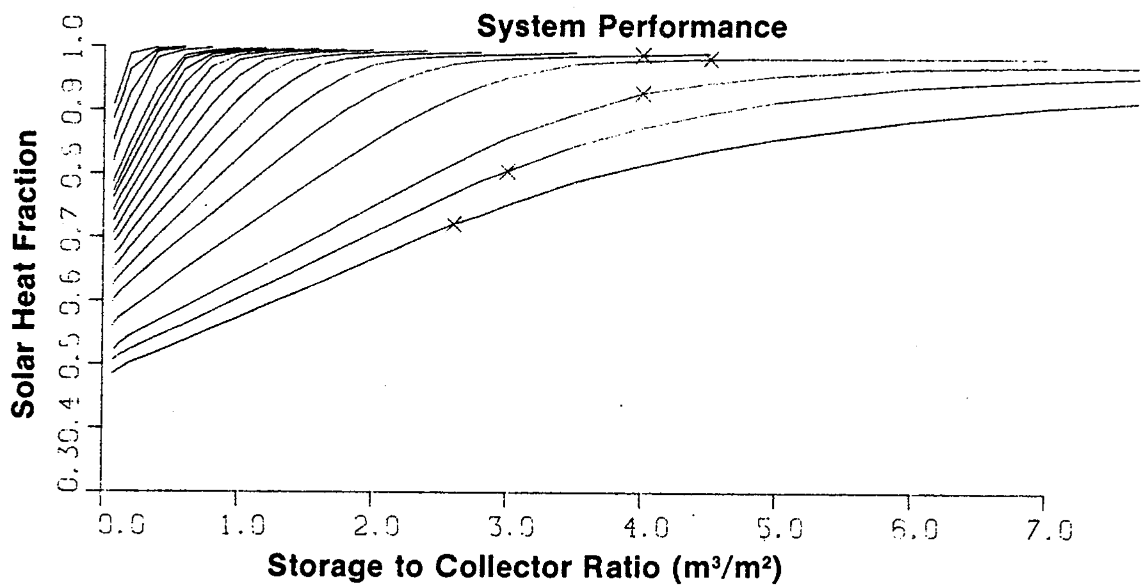
LOCATION: Boston, Mass.
LOAD TYPE: SUB-50, superinsulated load, space heat only.
SYSTEM TYPE: Evacuated tube collector, two-tank system.



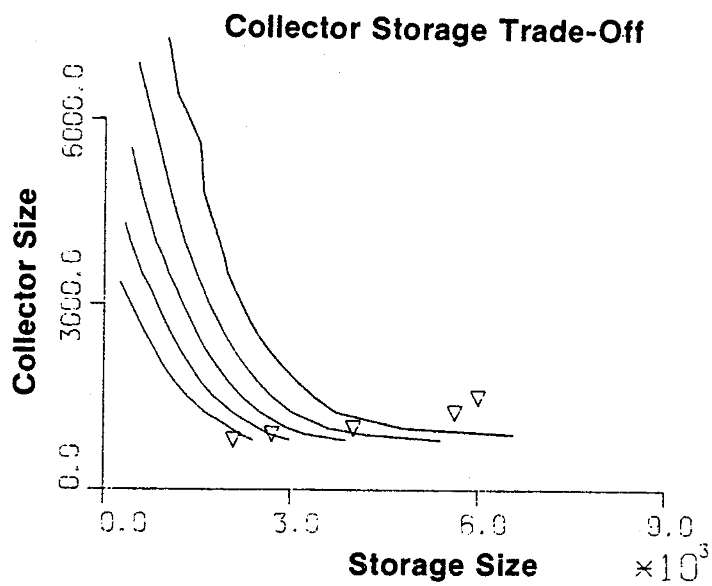
Collector Sizes (m²): 1600, 1800, 2000, 2400, 2800, 3200, 3600, 4000, 4400, 6800, 5200, 5600, 6000.



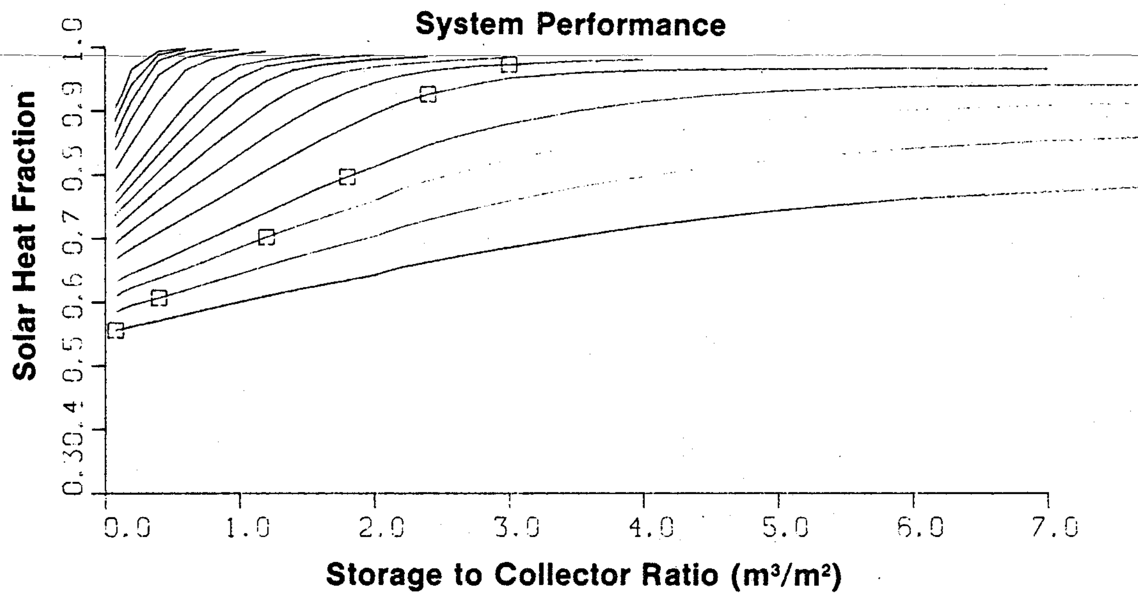
LOCATION: Medford, Ore.
LOAD TYPE: SUB-50, standard load, heat and hot water.
SYSTEM TYPE: Flat-plate collector, two-tank system.



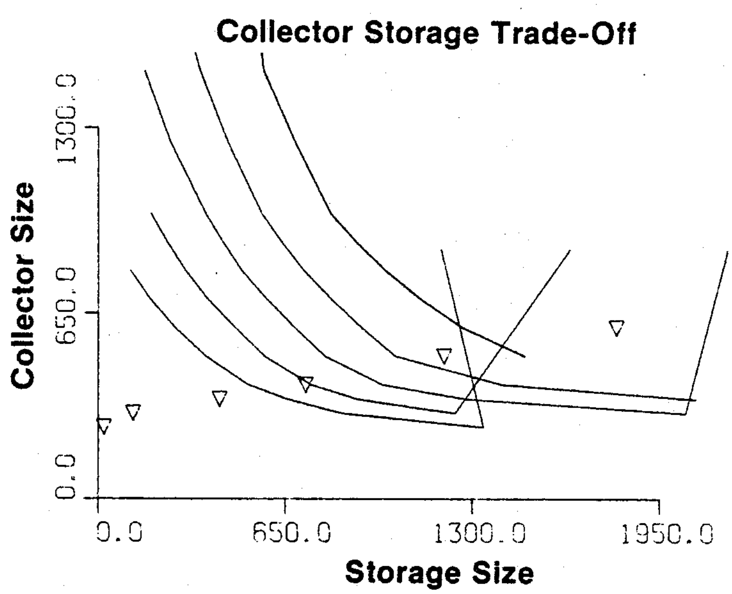
Collector Sizes (m²): 800, 900, 1000, 1250, 1500, 1750, 2000, 2250, 2500, 2750, 3000, 3250, 3500, 3750, 4000, 4800, 5600, 6400, 7200.



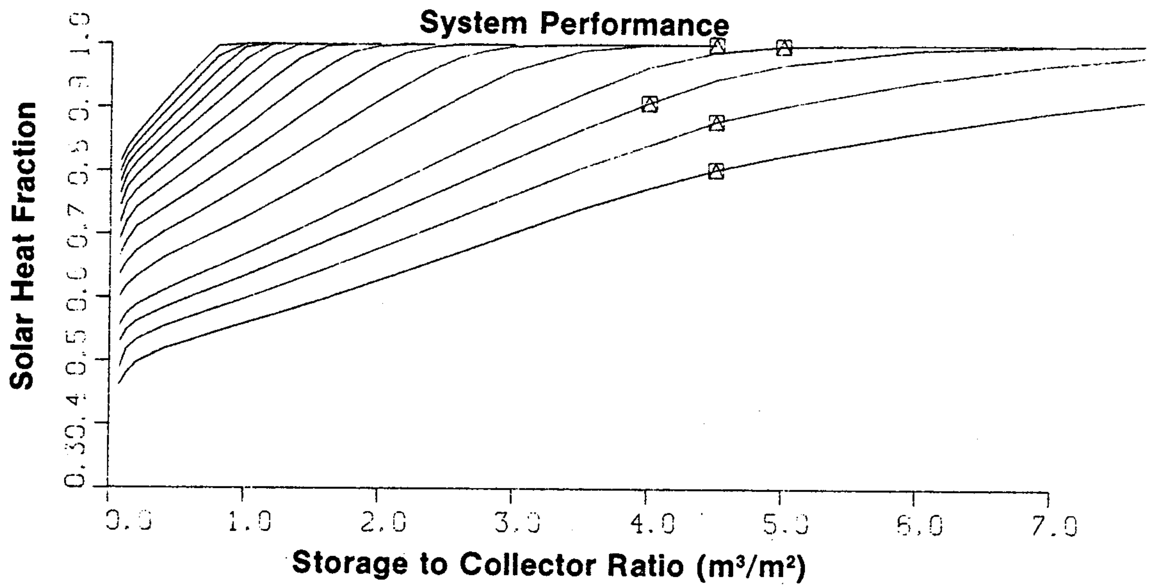
LOCATION: Medford, Ore.
LOAD TYPE: SUB-50, passive load, heat and hot water.
SYSTEM TYPE: Flat-plate collector, two-tank system.



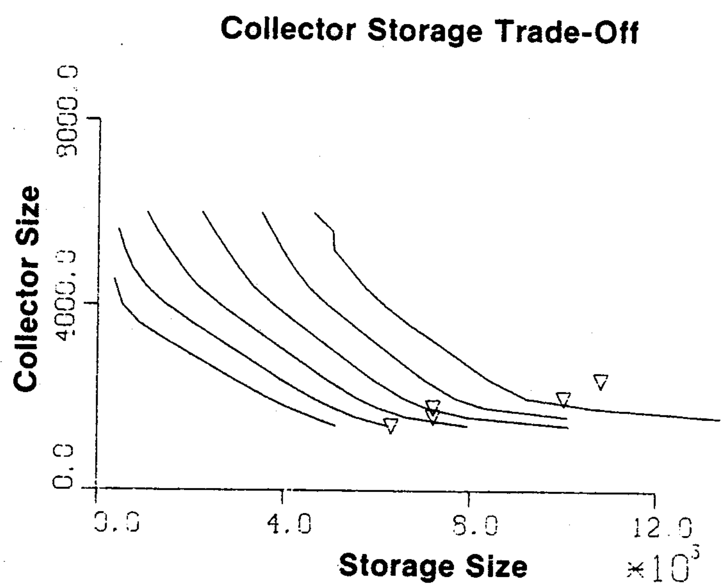
Collector sizes (m²): 250, 300, 350, 400, 500, 600, 700, 800, 900, 1000, 1250, 1500, 1750, 2000, 2250.



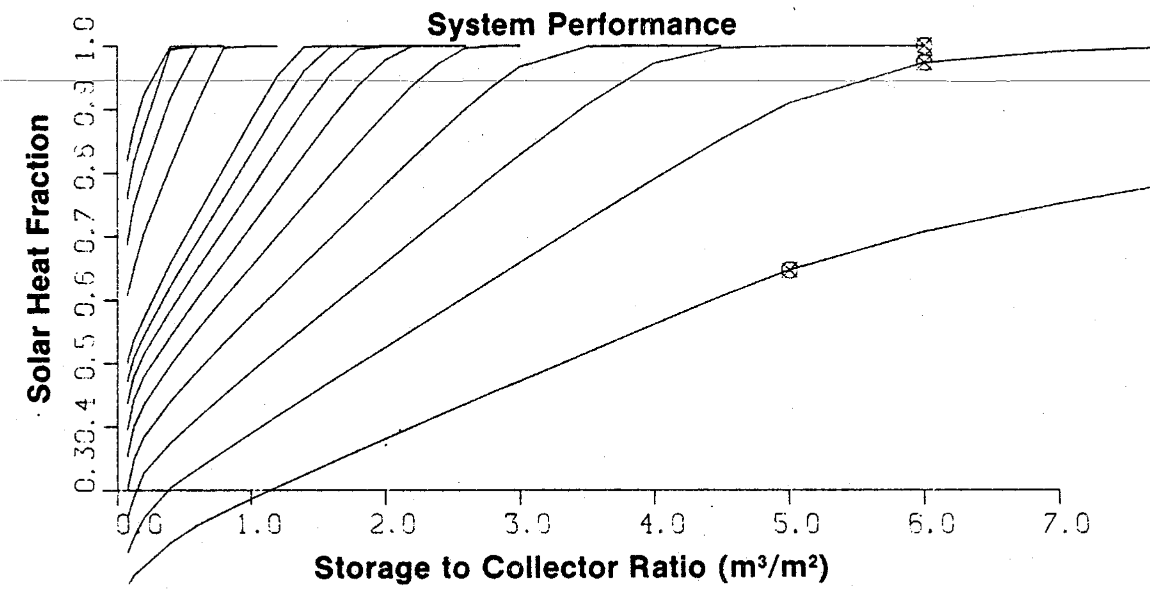
LOCATION: Medford, Ore.
LOAD TYPE: SUB-50, superinsulated load, heat and hot water.
SYSTEM TYPE: Flat-plate collector, two-tank system.



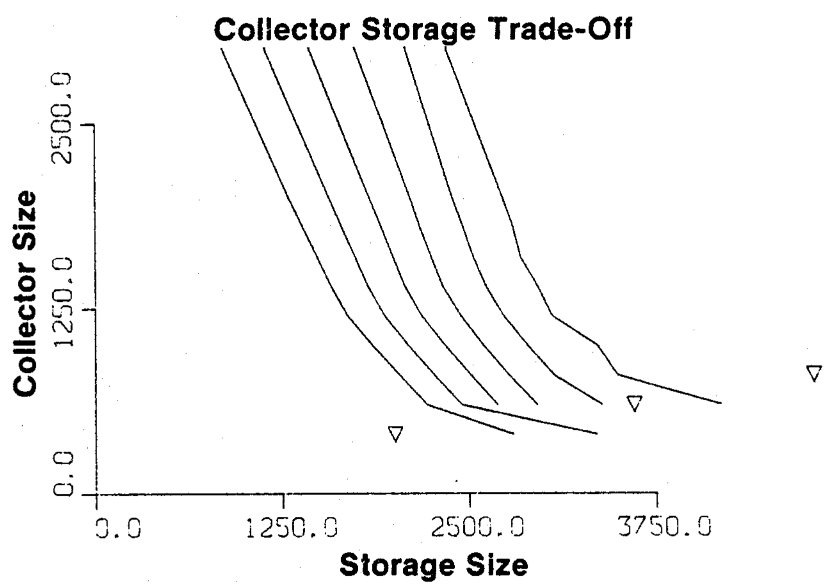
Collector sizes (m²): 1400, 1600, 1800, 2000, 2400, 2800, 3200, 3600, 4000, 4400, 4800, 5200, 5600, 6000.



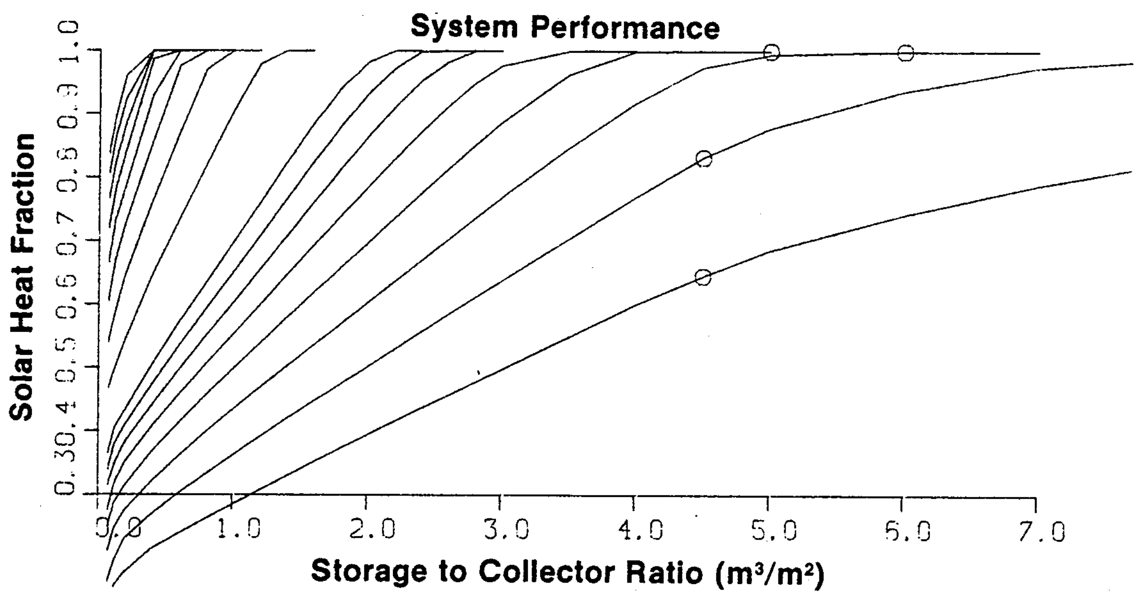
LOCATION: Medford, Ore.
LOAD TYPE: SUB-50, standard load, space heat only.
SYSTEM TYPE: Flat plate collector, single tank system.



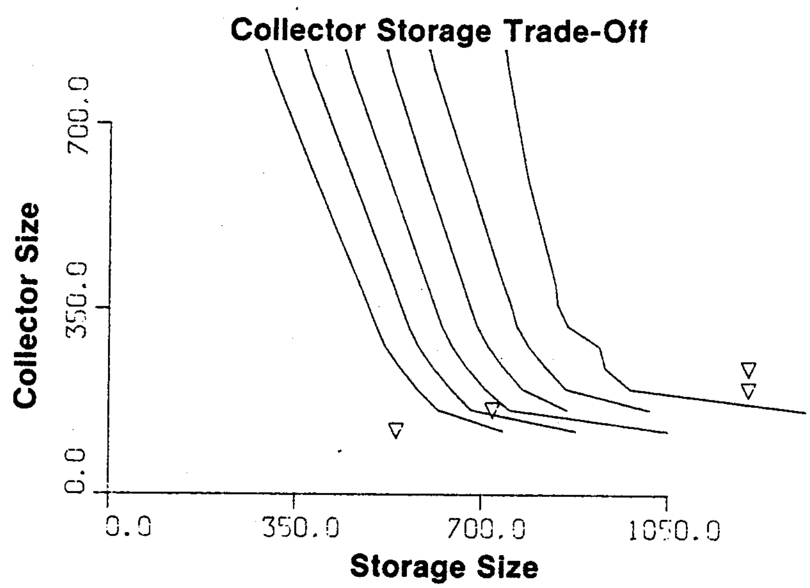
Collector sizes (m²): 400, 600, 800, 1000, 1200, 1400, 1600, 1800, 2000, 3000, 4000, 5000, 6000.



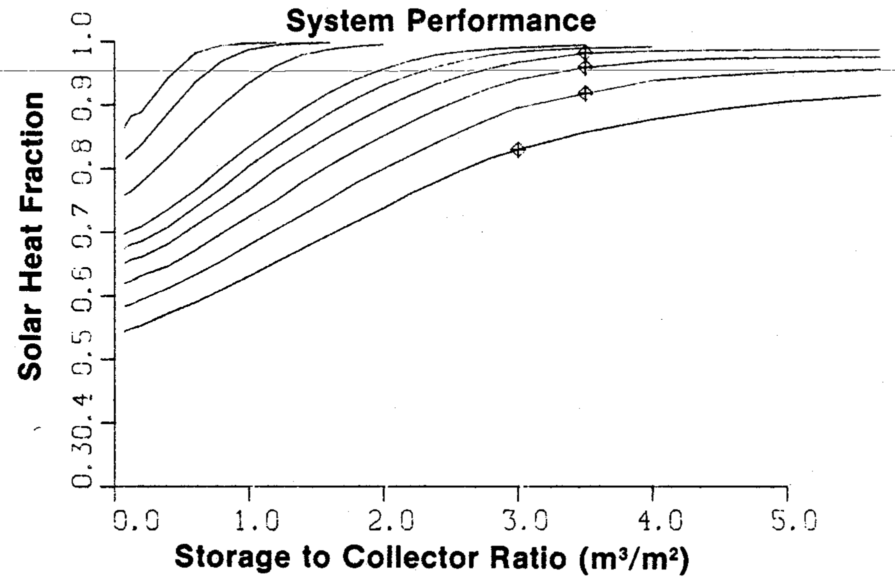
LOCATION: Medford, Ore.
LOAD TYPE: SUB-50, passive load, space heat only
SYSTEM TYPE: Flat-plate collector, single tank system.



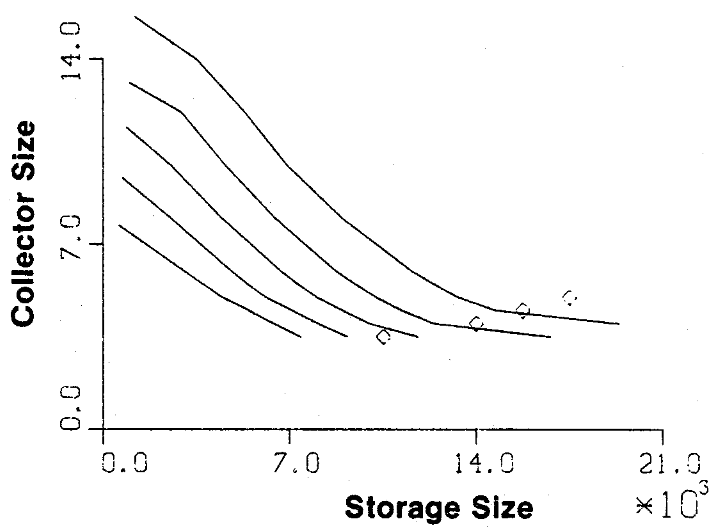
Collector sizes (m²): 120, 160, 200, 240, 280, 320, 360, 400, 600, 800, 1000, 1200, 1400, 1600, 1800, 2000.



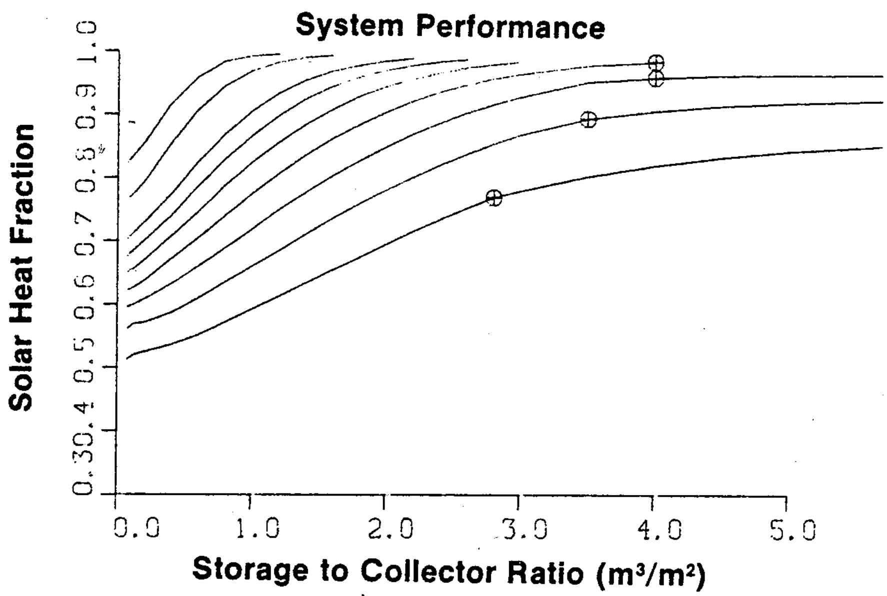
LOCATION: Medford, Ore.
LOAD TYPE: SUB-50, superinsulated load, space heat only
SYSTEM TYPE: Flat-plate collector, single tank system.



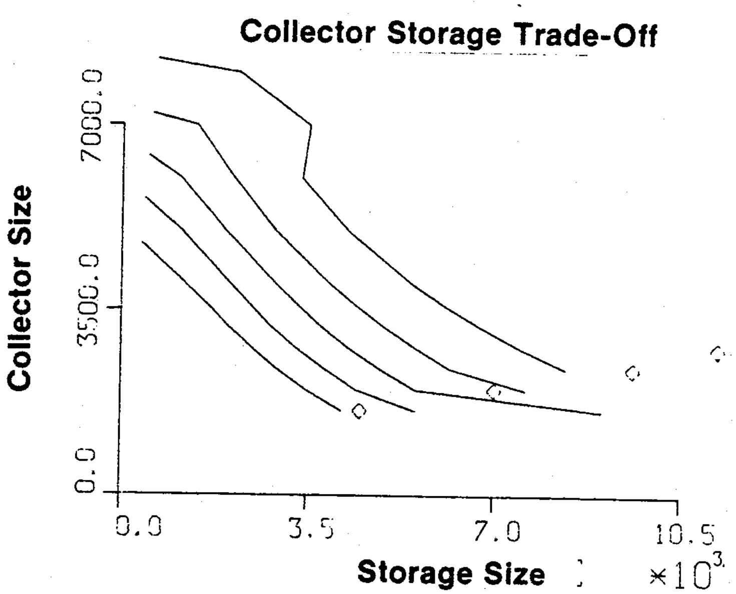
Collector sizes (m²): 3500, 4000, 4500, 5000, 5500, 6000, 8000, 10,000, 12,000.



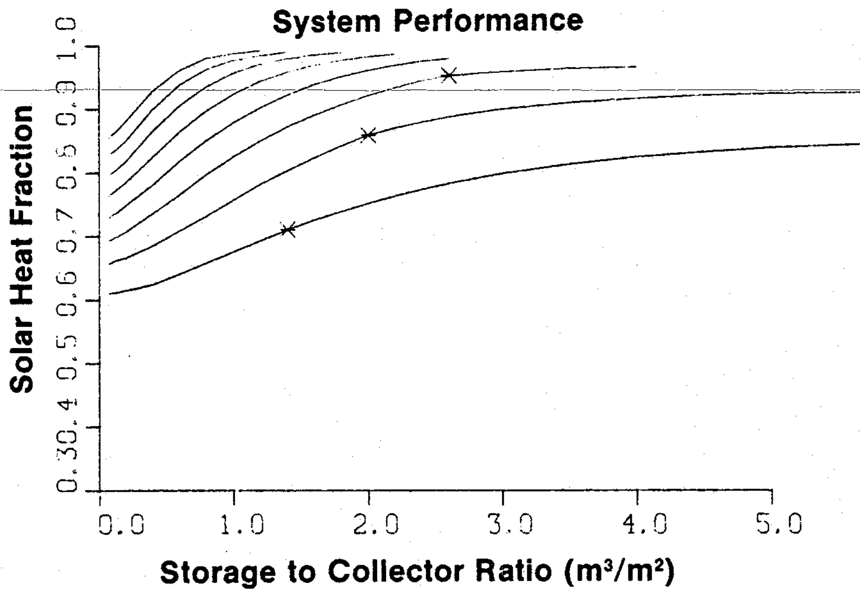
LOCATION: Bismarck, N.D.
LOAD TYPE: SUB-50, standard load, heat and hot water.
SYSTEM TYPE: Flat-plate collector, two-tank system.



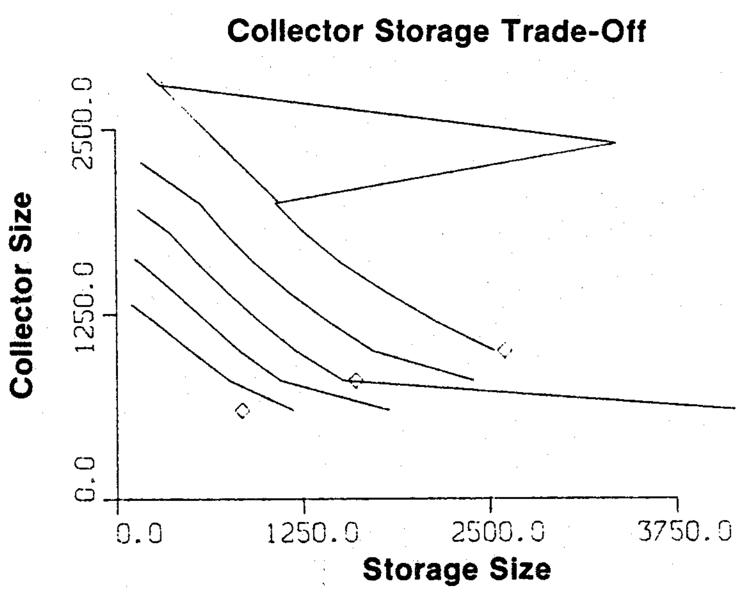
Collector sizes (m²): 1600, 2000, 2400, 2800, 3200, 3600, 4000, 5000, 6000, 7000.



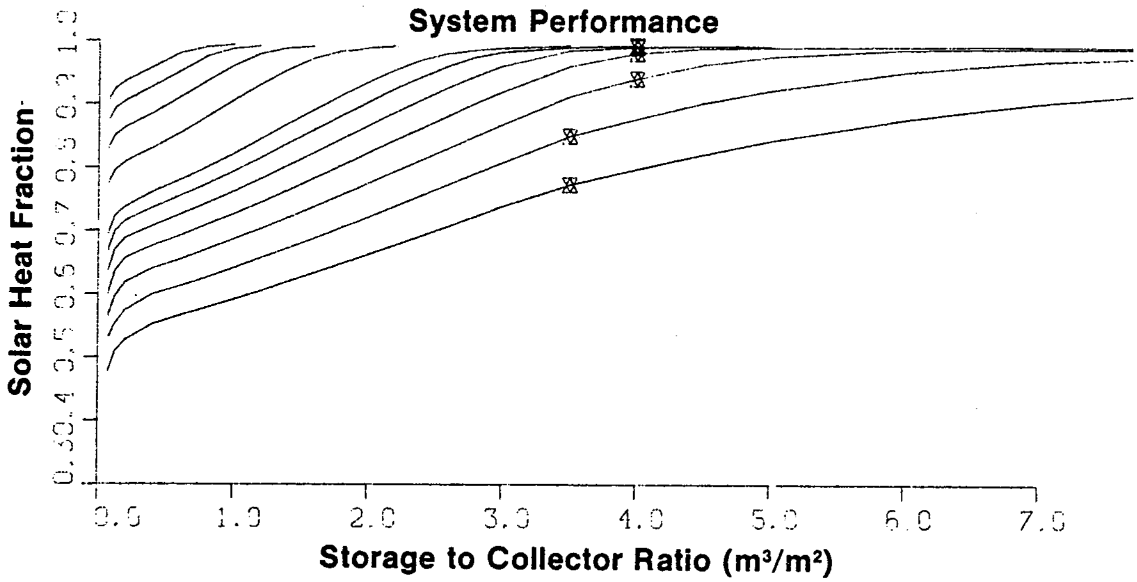
LOCATION: Bismarck, N.D.
LOAD TYPE: SUB-50, passive load, heat and hot water.
SYSTEM TYPE: Flat-plate collector, two-tank system.



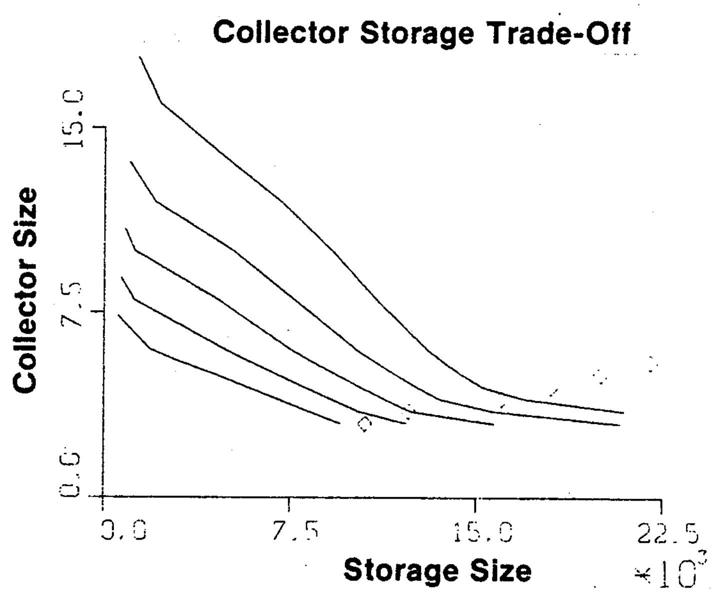
Collector sizes (m²): 600, 800, 1000, 1200, 1400, 1600, 1800, 2000.



LOCATION: Bismarck, N.D.
LOAD TYPE: SUB-50, superinsulated load, heat and hot water.
SYSTEM TYPE: Flat-plate collector, two-tank system.

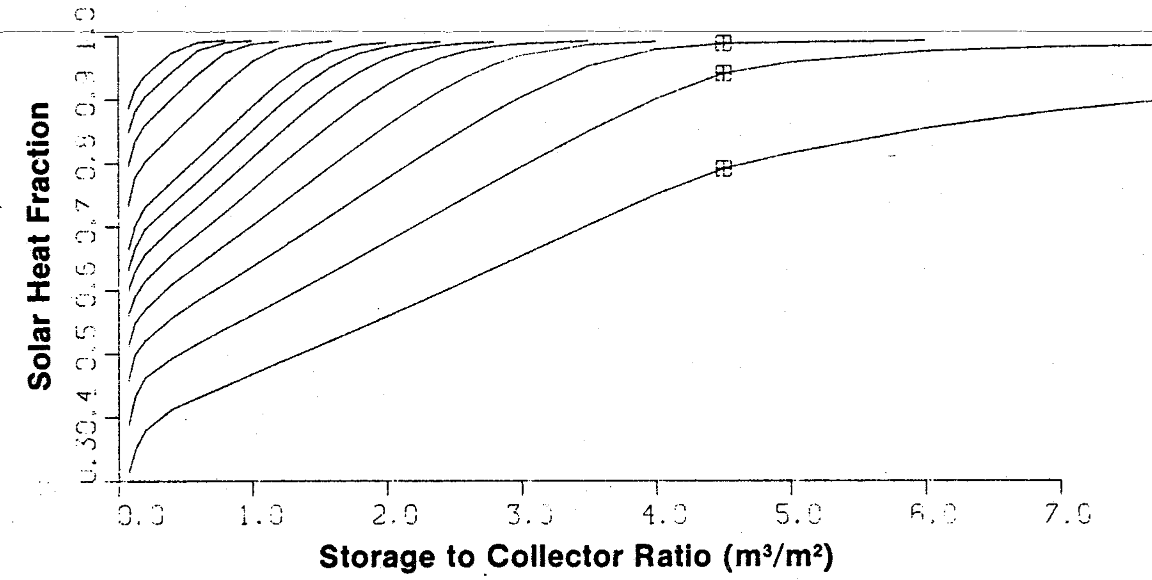


Collector sizes (m²): 3000, 3500, 4000, 4500, 5000, 5500, 6000, 8000, 10,000, 12,000, 14,000.



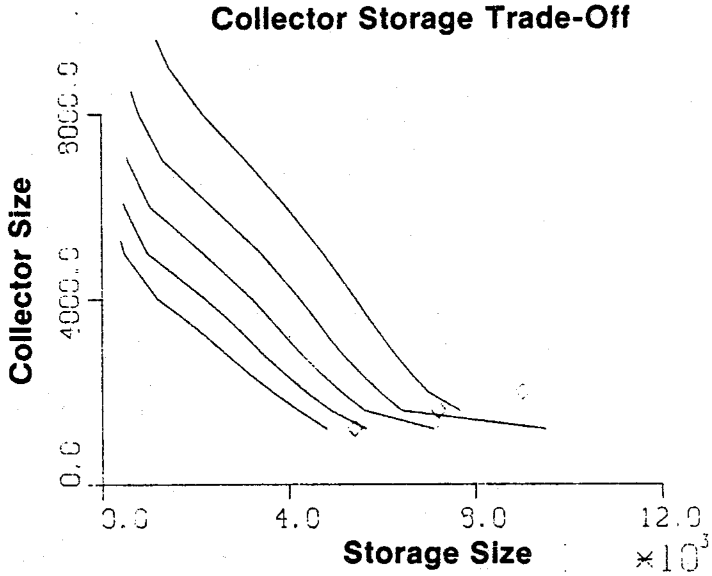
LOCATION: Bismarck, N.D.
LOAD TYPE: SUB-50, standard load, space heat only.
SYSTEM TYPE: Flat-plate collector, single-tank system.

System Performance

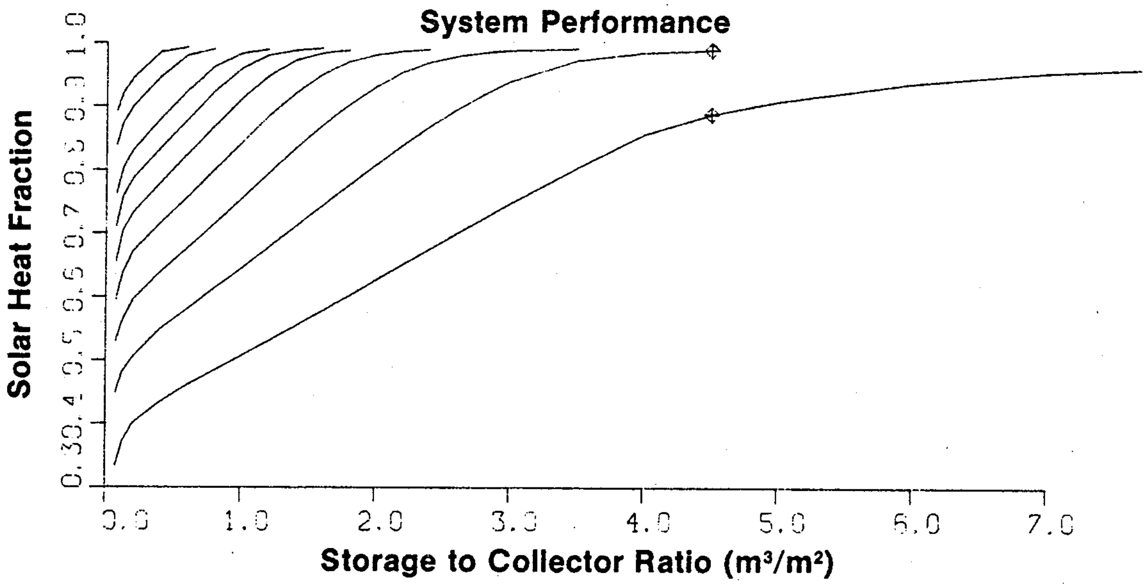


Collector sizes (m^2): 1200, 1600, 2000, 2400, 2800, 3200, 3600, 4000, 5000, 6000, 7000, 8000.

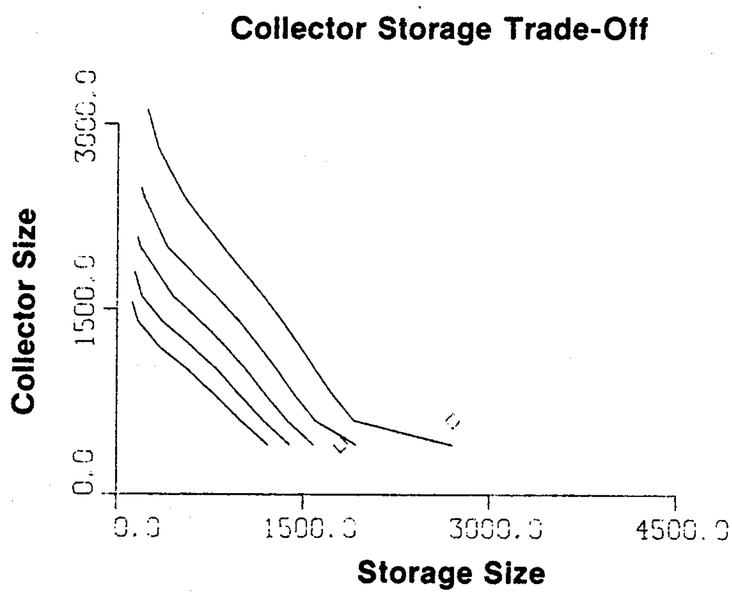
Collector Storage Trade-Off



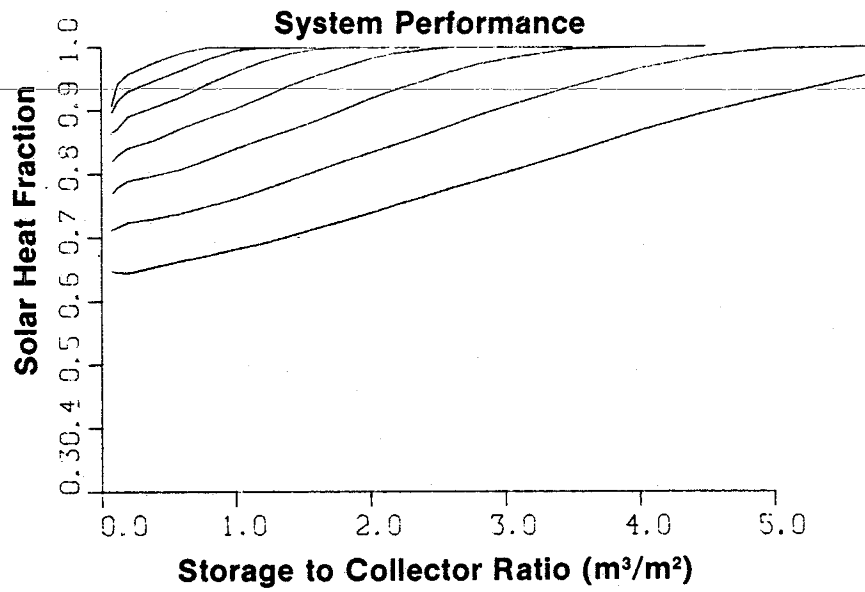
LOCATION: Bismarck, N.D.
LOAD TYPE: SUB-50 passive load, space heat only.
SYSTEM TYPE: Flat plate collector, single tank system.



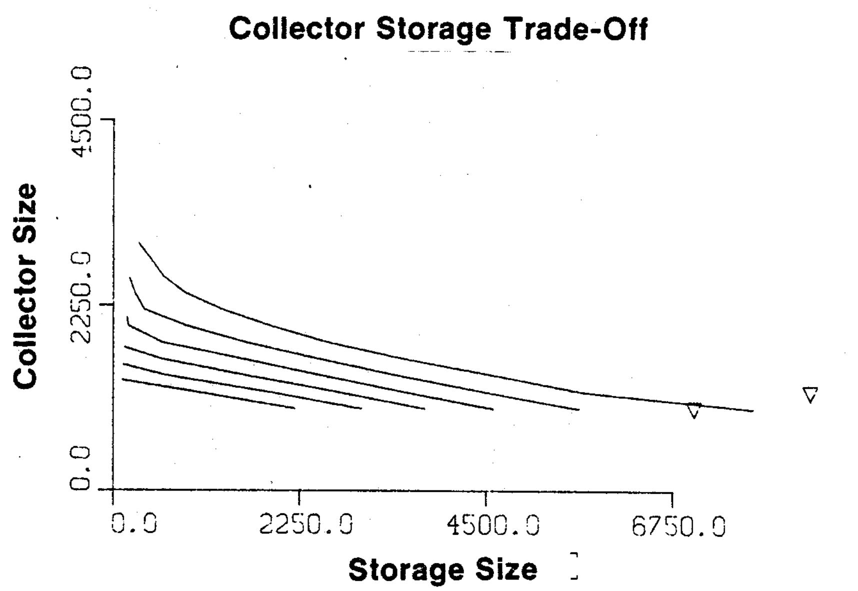
Collector sizes (m²): 400, 600, 800, 1000, 1200, 1400, 1600, 2000, 2400.



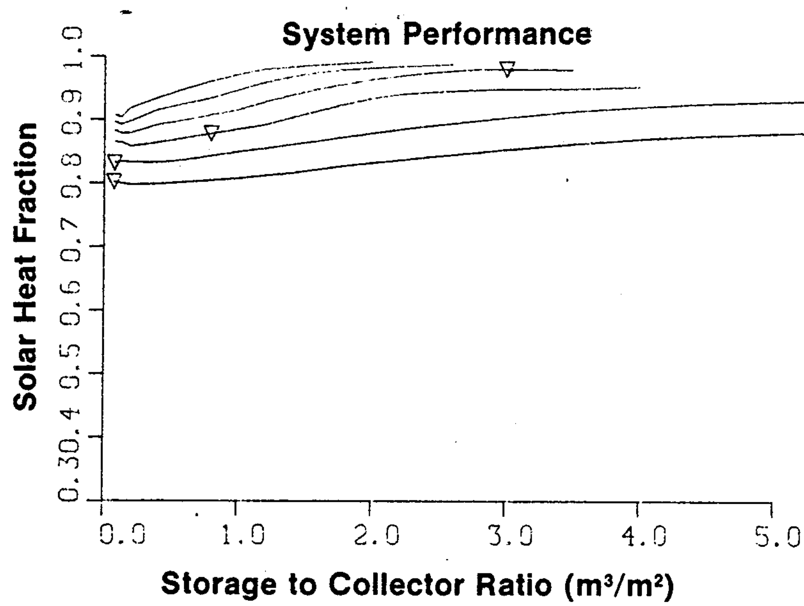
LOCATION: Bismarck, N.D.
LOAD TYPE: SUB-50, superinsulated load, space heat only.
SYSTEM TYPE: Flat-plate collector, single-tank system.



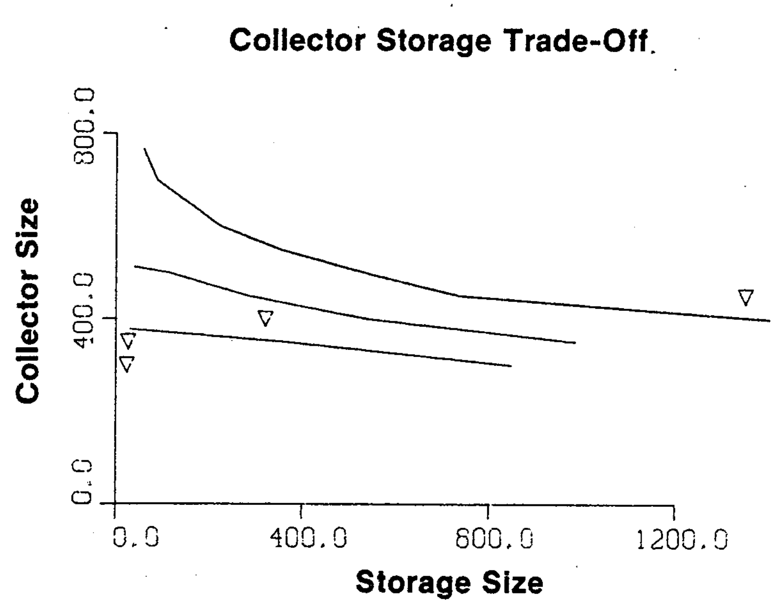
Collector sizes (m²): 1000, 1200, 1400, 1600, 1800, 2000, 2200.



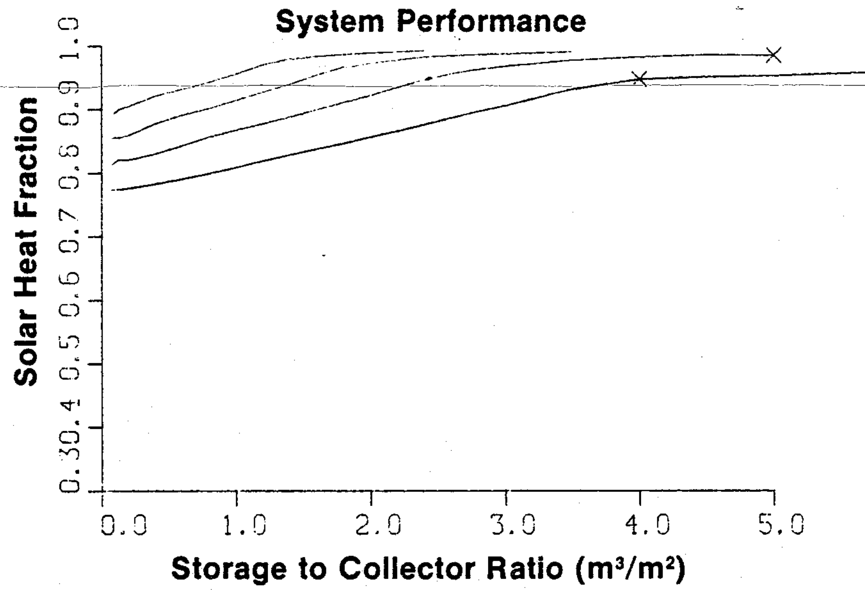
LOCATION: Albuquerque, N.M.
LOAD TYPE: SUB-50, standard load, space heat only.
SYSTEM TYPE: Flat-plate collector, two-tank system.



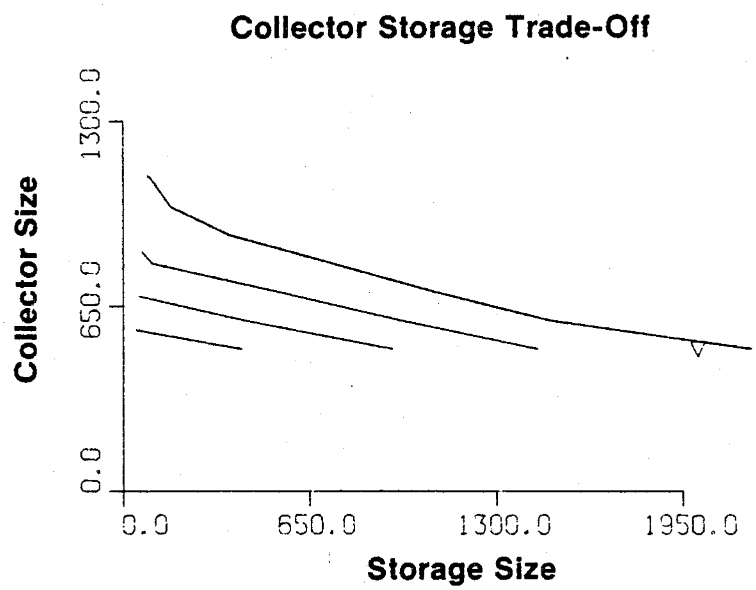
Collector sizes (m²): 300, 350, 400, 450, 500, 600.



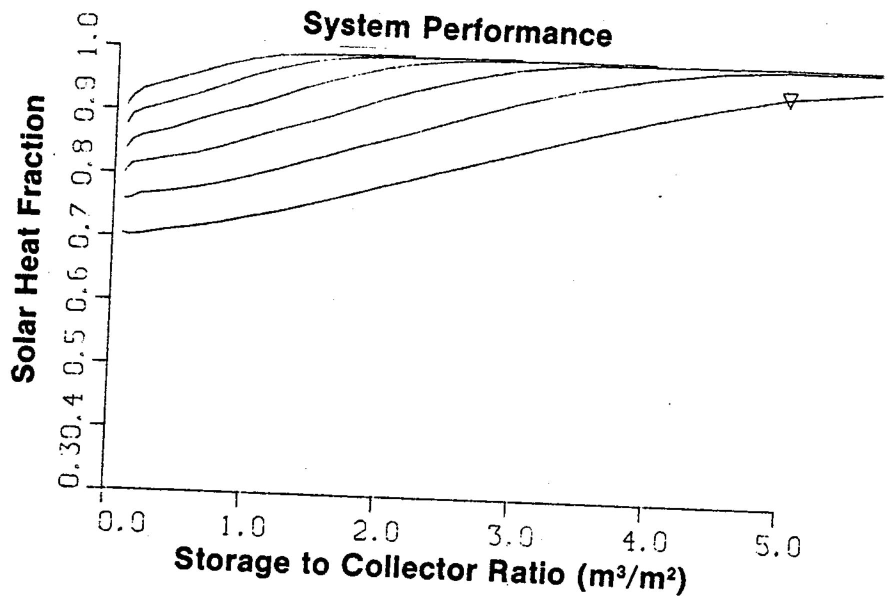
LOCATION: Albuquerque, N.M.
LOAD TYPE: SUB-50, passive load, heat and hot water.
SYSTEM TYPE: Flat-plate collector, two tank system.



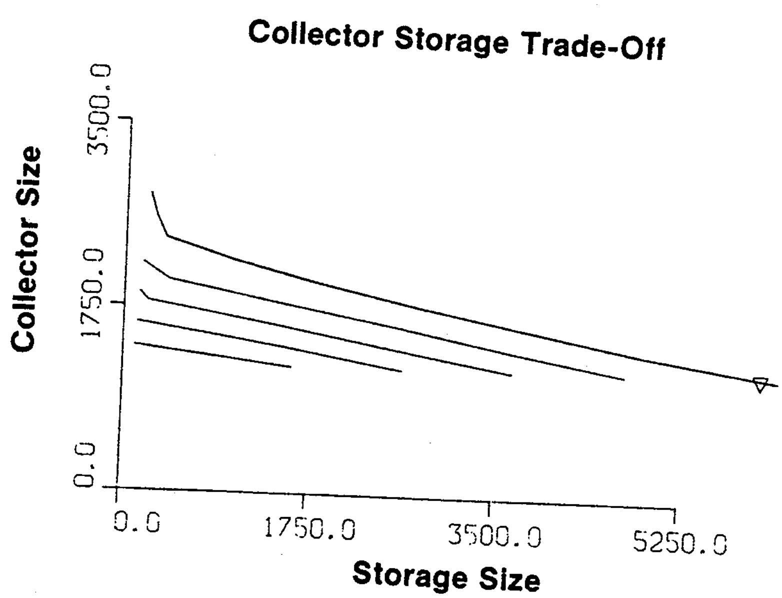
Collector sizes (m²): 500, 600, 700, 800.



LOCATION: Albuquerque, N.M.
LOAD TYPE: SUB-50, semi-passive load, heat and hot water.
SYSTEM TYPE: Flat plate collector, two tank system.



Collector sizes (m²): 1200, 1400, 1600, 1800, 2000, 2200.



LOCATION: Albuquerque, N.M.
LOAD TYPE: SUB-50, standard load, heat and hot water.
SYSTEM TYPE: Flat-plate collector, two-tank system.